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# Cycloastragenol, a Triterpenoid Saponin, Regulates Oxidative Stress, Neurotrophic Dysfunctions, Neuroinflammation and Apoptotic Cell Death in Neurodegenerative Conditions

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**Abstract:** Here, we have unveiled the effects of cycloastragenol against A $\beta$  (Amyloid-beta)-induced oxidative stress, neurogenic dysfunction, activated mitogen-activated protein (MAP) kinases, and mitochondrial apoptosis in an A $\beta$ -induced mouse model of Alzheimer's disease (AD). The A $\beta$ -induced mouse model was developed by the stereotaxic injection of amyloid-beta (5  $\mu$ g/mouse/intracerebroventricular), and cycloastragenol was given at a dose of 20 mg/kg/day/p.o for 6 weeks daily. For the biochemical analysis, we used immunofluorescence and Western blotting. Our findings showed that the injection of A $\beta$  elevated oxidative stress and reduced the expression of neurogenic markers, as shown by the reduced expression of brain-derived neurotrophic factor (BDNF) and the phosphorylation of its specific receptor tropomyosin receptor kinase B (p-TrkB). In addition, there was a marked reduction in the expression of NeuN (neuronal nuclear protein) in the A $\beta$ -injected mice brains (cortex and hippocampus). Interestingly, the expression of Nrf2 (nuclear factor erythroid 2-related factor 2), HO-1 (heme oxygenase-1), p-TrkB, BDNF, and NeuN was markedly enhanced in the A $\beta$  + Cycloastragenol co-treated mice brains. We have also evaluated the expressions of MAP kinases such as phospho c-Jun-N-terminal kinase (p-JNK), p-38, and phospho-extracellular signal-related kinase (ERK1/2) in the experimental groups, which suggested that the expression of p-JNK, p-P-38, and p-Erk were significantly upregulated in the A $\beta$ -injected mice brains; interestingly, these markers were downregulated in the A $\beta$  + Cycloastragenol co-treated mice brains. We also checked the expression of activated microglia and inflammatory cytokines, which showed that cycloastragenol reduced the activated microglia and inflammatory cytokines. Moreover, we evaluated the effects of cycloastragenol against mitochondrial apoptosis and memory dysfunctions in the experimental groups. The findings showed significant regulatory effects against apoptosis and memory dysfunction as revealed by the Morris water maze (MWM) test. Collectively, the findings suggested that cycloastragenol regulates oxidative stress, neurotrophic processes, neuroinflammation, apoptotic cell death, and memory impairment in the mouse model of AD.

**Keywords:** Alzheimer's disease; Amyloid-beta; neurogenesis; neuroprotection; neurodegeneration

## 1. Introduction

Alzheimer's is a neurodegenerative disorder linked with cognitive and memory dysfunction, although other clinical symptoms are also recognized. The pathological basis of the disease has been known for more than a hundred years, and the presence of the

neurofibrillary tangles and amyloid-beta ( $A\beta$ ) plaques are still used for its diagnosis [1]. In addition to the  $A\beta$  accumulation and hyperphosphorylation of tau, there are several other pathological hallmarks of AD, which are elevated oxidative stress, neuroinflammation, loss of normal neurogenic processes, and apoptotic cell death [2].

A reported mechanism for the pathogenic role of oxidative stress in the execution of neurodegeneration is the suppression of nuclear factor erythroid-2 related factor-2 (NRF2), which upon binding with antioxidant genes activates a plethora of cytoprotective genes against elevated oxidative insult [3,4]. Several studies have strongly unveiled the role of Nrf2 in the pathophysiology of AD-related neurodegeneration [5,6]. Elevated oxidative stress is responsible for the dysregulation of several physiological phenomena in the central nervous system, such as neurogenesis, inflammatory mediators, and mitochondrial homeostasis [7]. The hippocampus possesses the most unique characteristic of neuronal cells renewal, called adult hippocampal neurogenesis (AHN), which continues throughout the life of an individual [8], providing neural plasticity to the hippocampus [9]. Research has been attributed to unveil the role of hippocampal neurogenesis and its role in the pathological mechanisms of neurodegeneration. Some known factors that play a role in the neurogenic processes are tropomyosin-receptor kinase B (TrkB), brain-derived neurotrophic factor (BDNF), and cAMP-response element-binding protein (CREB). The most studied factor in the neurogenic processes is BDNF, which is a growth factor and classified under the neurotrophin family. The neurotrophins are secreted proteins that are potential regulators of neuronal survival, growth, development, and neurogenesis modulators [10], and they are ubiquitously expressed in the brain [11]. A body of evidence suggests the involvement of BDNF in a variety of physiological functions of the brain. Its functions differ, depending on the stage of brain development and compartment of the brain, such as glial, neuronal, or vascular constituent of the brain. The critical effects of BDNF are developmental processes, synaptogenesis, neuroprotection, and the control of synaptic interactions that affect memory and cognitive functions [12,13]. Another main factor in the memory and neuronal cells' survival is CREB, which is known for the formation of cognitive and memory functions [14]. The phosphorylation of CREB, followed by the activation of CREB-binding protein (CBP) and p300, allows the transcriptional activation of other genes such as Egr-1 (zif268), which are essential for cognitive functions [15]. It has been reported that the dysfunction of the CREB signaling in AD mouse models [16,17] and regulation of the phosphorylation of CREB has shown promising rescuing effects against neuroinflammation and memory dysfunction, as the phosphorylated CREB has been suggested to inhibit the phosphorylation of NF- $\kappa$ B by reducing the binding of CBP to the NF- $\kappa$ B, where it will reduce the pro-inflammatory processes [18].

Moreover, the elevated oxidative stress also induces neuroinflammation [19]. Since the start of the 21st century, protein kinases have become the accepted targets for the management of neurodegenerative diseases [20]. However, the application of drugs targeting the protein kinases is limited in use, despite its critical role in various pathological processes. One of the known kinases is mitogen-activated protein kinase (MAPK), which has drawn much attention due to its prominent roles in several cellular processes including differentiation, cell survival, mitogenesis, and apoptotic cell death [21]. The known members of the MAP kinases are c-Jun N-terminal kinase (JNK), p-38, and extracellular signal-regulated kinase (ERK). Previous studies have suggested elevated expression of MAP kinases in AD and other neurodegenerative conditions, and the intervention in the activation of MAP kinases has shown promising therapeutic effects [22,23].

In addition, the elevated oxidative stress is closely associated with activation of the astrocytes (GFAP: Glial Fibrillary Acidic Protein) and microglia (Iba-1: ionized calcium-binding adapter molecule-1), which facilitates the release of inflammatory cytokines [24]. The GFAP is the protein in astrocytes, which is a type of glial cells in the central nervous system (CNS). Astrocytes have a range of control and homeostatic functions in health and disease. Astrocytes assume a reactive phenotype in neurodegenerative conditions [25]. Ionized binding protein1 (Iba-1), a calcium-binding EF-hand protein, regulates the release

of inflammatory cytokines, cell migration, and phagocytosis. The Iba-1 expression has been useful to study the pathophysiological role of activated microglia in the neurodegenerative conditions [26].

The known contributing cytokines are tumor factor-alpha (TNF- $\alpha$ ) and interleukin 1-beta (IL-1 $\beta$ ). The release of inflammatory cytokines further aggravates the neurodegeneration by activation of the mitochondrial apoptosis [27], which is executed by several factors, such as Caspases [28], BCL-XS, and Bax, a pro-apoptotic factor. The B cell lymphoma/leukemia-2 protein (Bcl-2) and Bcl-XL are anti-apoptotic factors [29]. Different therapeutic approaches have been conducted to reduce the overall cell death mechanisms in neurodegenerative diseases.

Recently, phytonutrients have attracted much interest due to their safety and efficacy. One of the keys and recently identified compounds is cycloastragenol (CAG), which is a potent telomerase activator that has conferred neuroprotection against different neurodegenerative conditions [30] and was extracted from *Astragalus radix*. *Astragalus radix* is a Chinese herbal medicine commonly used for the management of various diseases, such as cardiovascular diseases, diabetes, and cancers in China [31]. In addition, Astragaloside-IV is an active component of *Astragalus radix*, which is responsible for its known pharmacological effects. Most of the Astragaloside-IV is converted to cycloastragenol in vivo [32]. Therefore, CAG is regarded as an active form of astragaloside IV [12]. CAG has shown several beneficial effects, including antioxidant [33], anti-aging, anti-apoptotic, and anti-inflammatory effects [34].

The effects of cycloastragenol against the A $\beta$ -induced elevated oxidative stress, defects in neurogenic functions, neuroinflammation, and apoptotic cell death are still elusive. Therefore, in the current study, we have hypothesized that the potential antioxidants in cycloastragenol may rescue the mice brains against AD-associated altered neurogenic processes, activation of the MAP kinases, and execution of the apoptotic cell death in the A $\beta$ -injected mice brains.

To analyze the effects of cycloastragenol against AD-related pathological changes in the mice, we developed a mouse model of Alzheimer's disease by intracerebroventricular injection of A $\beta$  into the mice brains by using a stereotaxic frame. Graphically, the study design and mechanisms have been shown in the last figure.

## 2. Materials and Methods

### 2.1. Experimental Mice

For the development of the Alzheimer's disease mouse model, the A $\beta$ <sub>1-42</sub> peptide was injected as a single injection (intracerebroventricular) into the mice (C57BL/6N) brain by using a Hamilton syringe in stereotaxic procedures. The male mice had an average age of 10 weeks, and they were obtained from the Samtako Bio Labs Ulsan Republic of Korea, kept at room temperature (23  $\pm$  2  $^{\circ}$ C), under a 12 h light–dark cycle, and food and water were freely provided. The animals were handled according to the approved guidelines (Approval ID: 125) of the Division of Applied Life Sciences, Gyeongsang National University, Jinju, Korea.

### 2.2. Preparation and Intracerebroventricular (i.c.v) Injection of A $\beta$ <sub>1-42</sub>

The human A $\beta$ <sub>1-42</sub> peptide was made as 1 mg/mL in normal saline and incubated for four days at 37  $^{\circ}$ C [35]. For the surgery and intracerebroventricular injection of A $\beta$ <sub>1-42</sub>, the mice were anesthetized (0.05 mL/100 g body weight Rompun and 0.1 mL/100 gm body weight) with tiletamine hydrochloride (0.05 mL/100 g body weight) and zolazepam hydrochloride (Zoltil) (0.1 mL/100 g body weight) and fixed in a stereo frame. For the maintenance of body temperature, a heating pad was used. The coordinates for the injection were fixed from the bregma point (–0.2 mm anteroposterior (AP), 1 mm mediolateral (ML), and –2.4 mm dorsoventral (DV) to Bregma) by using the Franklin and Paxinos mouse brain atlas. Five microliters of the solution containing a total of 5  $\mu$ g of A $\beta$ <sub>1-42</sub> was slowly injected by using a Hamilton micro-syringe, 2.4, and the skin was sutured.

### 2.3. Mice Grouping and Drugs Treatment

After 24 h of the A $\beta$ <sub>1-42</sub> injection, the mice were separated into four groups (16 mice per group, excluding the dead mice during the surgery): Control Group (Saline injected), A $\beta$ <sub>1-42</sub> injected mice, A $\beta$ <sub>1-42</sub> + Cycloastragenol 20 mg/kg, and Cycloastragenol 20 mg/kg alone treated mice. Cycloastragenol (CAG), having purity > 98%, (Sigma-Aldrich, Burlington, MA, USA) was prepared in 5% DMSO and diluted with 2% Tween-20 in PBS. Cycloastragenol was administered orally by using 20–25 gauge  $\times$  1.5 inches curved dosing cannula at a dose of 20 mg/kg/day for 6 weeks, as suggested previously [36].

### 2.4. Proteins Collection and Quantification

For the collection of proteins, the tissue lysates were homogenized in PRO-PREP™ extraction solution (iNtRON Biotechnology, Inc., Sungnam, Korea) and centrifuged at 14,000 rpm for 25 min at 4 °C (Eppendorf 5415R). The supernatant was collected and used for the Western blotting.

### 2.5. Western Blot Analysis

The concentrations of protein were analyzed by using the Bio-Rad Assay kit (Bio-Rad Laboratories, Hercules, CA, USA), as conducted previously [37,38]. The samples were loaded in a sodium dodecyl polyacrylamide gel (SDS PAGE Gel), with a pre-stained protein marker (GangNam-STAIN, iNtRON Biotechnology, Seoul, Korea). After running, the proteins were transferred to PVDF (polyvinylidene fluoride membrane) membranes (Immobilon-PSQ, Merck Millipore, Burlington, MA, USA) and blocked with 5% skim milk. After treatment with appropriate primary and secondary antibodies, the bands were visualized with an ECL (enhanced chemiluminescent) detection reagent (EzWestLumiOne, ATTO, Tokyo, Japan).  $\beta$ -Actin was used as a loading control, and the results have been presented in terms of fold change.

### 2.6. Samples Preparation for the Immunofluorescence Analysis

The mice were anesthetized with Rompun and Zoltil as described in Section 2.2. The anesthetized mice were transcardially perfused with normal saline (flow rate of 10 mL/min for 3 min), followed by infusion with 4% paraformaldehyde for 8 min using a peristaltic pump. The brains were separated and fixed for 48 h in 4% cold neutral buffer paraformaldehyde, which is followed by treatment with 30% sucrose for 48 h, rinsed, and fixed in OCT (optimal cutting temperature compound) compound (Sakura, Torrance, CA, USA). By using a microtome (Leica cryostat CM 3050S, Nussloch, Germany), 14  $\mu$ m sections were obtained on glycine-coated slides (Fisher, Pittsburgh, PA, USA).

### 2.7. Antibodies and Reagents

The following main reagents and antibodies are used in the current studies: cycloastragenol from Sigma Aldrich (CAS Number-78574-94-4), Nrf-2 (sc-722), HO-1 (sc-136,961), p-TrkB (sc-365842), TrkB (sc-376776), BDNF (sc-546), p-anti-p-38 (9212S), anti-p-p-38 (9211S), JNK (sc-6254), JNK (sc-7345), Caspase-3 (sc-7272), Bax (sc-7480), Bcl2 (sc-7382), Iba-1 (sc-32725), GFAP (sc-33673), TNF- $\alpha$  (sc-52746), IL-1 $\beta$  (sc-32294), Cleaved Caspase-3 (#9664), Bim (sc-374358), and  $\beta$ -actin (sc-47,778) from Santa Cruz Biotechnology (Dallas, TX, USA). In addition, p-CREB (#87G3), CREB (#48H2), NeuN (sc-33684), p-ERK (#9101), and ERK (#9102) antibodies were obtained from Cell Signaling Technology (Danvers, MA, USA). Secondary anti-mouse HRP (horseradish peroxidase) conjugated (Promega Ref# W402) and anti-rabbit HRP conjugated (Promega Ref# W401) were diluted 1:10,000 in 1  $\times$  TBST. For the immunofluorescence analysis, the secondary FITC or TRITC conjugated secondary antibodies were used, which were goat anti-mouse (Ref# A11029) and goat anti-rabbit (Ref# 32732).

### 2.8. Immunofluorescence Analysis

For the confocal microscopic studies, the slides were washed, incubated with proteinase-k for 5 min, and afterwards incubated with normal goat serum containing 0.02% Triton and 0.01 g/mL bovine serum albumin for 45 min. After blocking, the slides were reacted with the required primary antibodies (overnight at 4 °C). After treatment of the primary antibodies, the slides were treated with appropriate rabbit/anti-mouse IgG (fluorescent FITC/TRITC labeled) secondary antibodies (diluted in 1:100 in 0.01 M PBS) (Invitrogen, Seoul, Korea) for 2 h at room temperature. For nuclear staining, the 4',6-diamidino-2-phenylindole (DAPI, 1:1000 in PBS) was used. After treatment of DAPI, the slides were covered with a coverslip, using a fluorescent mounting medium DAKO (S3023). The immunofluorescence reactivity of the total area assessed relative to a sub-threshold background was measured with Image J (v. 1.50, NIH, Bethesda, MD, USA).

### 2.9. ROS and LPO Assays In Vivo

The ROS (reactive oxygen species) were evaluated as described previously [39,40]. The ROS assay is based on the oxidation of 2',7'-dichlorodihydrofluorescein diacetate (DCFH-DA) to fluorescent 2',7'-dichlorofluorescein (DCF). To analyze the level of ROS, the brain homogenates of the cortex and hippocampus were diluted in Loke's buffer (1:20 ratio) to 5 mg tissue/mL concentration. Then, 1 mL of Loke's buffer, 0.2 mL of brain homogenate, and 10 mL of DCFH-DA (5 mM) were incubated at room temperature for 15 min to obtain a fluorescent DCF. The DCF level was measured via a microplate reader (excitation at 484/530 nm). Parallel blanks were used for monitoring the background fluorescence in the absence of DCF. The results have been shown as pmol DCF formed per minute per milligram of protein.

The LPO (lipid peroxidation) assay was conducted as described previously [41]. Here, the free Malondialdehyde (MDA), which is a marker of LPO was measured in the cortex and hippocampus using the MDA colorimetric/fluorometric kit (Cat #K739-100) per the instructions provided.

### 2.10. Morris Water Maze Test

The memory-related parameters were analyzed by using the Morris water maze (MWM) test by using video tracking software (SMART Panlab, Harvard Apparatus, Holliston, MA, USA), as performed previously [42,43]. After receiving 5 days of training, the latency (sec) to reach the platform was recorded. After completion of the training, the probe test was conducted to evaluate the memory formation by removing the platform and allowing the animal to swim freely for 1 min and reach the (previously placed) platform position. The number of crossings of the platform position, time spent in that specific quadrant, and latency to reach the position on day 6 were considered and presented graphically.

### 2.11. Data Analysis and Statistics

By using the ImageJ software, the relative densities of the Western blot bands were calculated and have been shown as "mean (SD)" of 8 mice/group for three repeated experiments (for Western blot and immunofluorescence). For comparison among the groups, one-way ANOVA followed by Bonferroni's multiple comparisons tests were used. The calculations were made with Prism 6 software (GraphPad Software, San Diego, CA, USA). The  $p$ -value <0.05 was set a significant difference. \*, a significant difference from the control group; # significant difference from the A $\beta$ -induced mice. Significant difference = \*  $p$  < 0.05; \*\*  $p$  < 0.01, #  $p$  < 0.05; and ##  $p$  < 0.01.

## 3. Results

### 3.1. Effects of Cycloastragenol against the Oxidative-Stress and Neurotrophic Factors in A $\beta$ -Injected Mice Brains

To analyze the effects of cycloastragenol against the elevated oxidative stress, we checked the expression of LPO and ROS in the brain homogenates, as suggested previ-

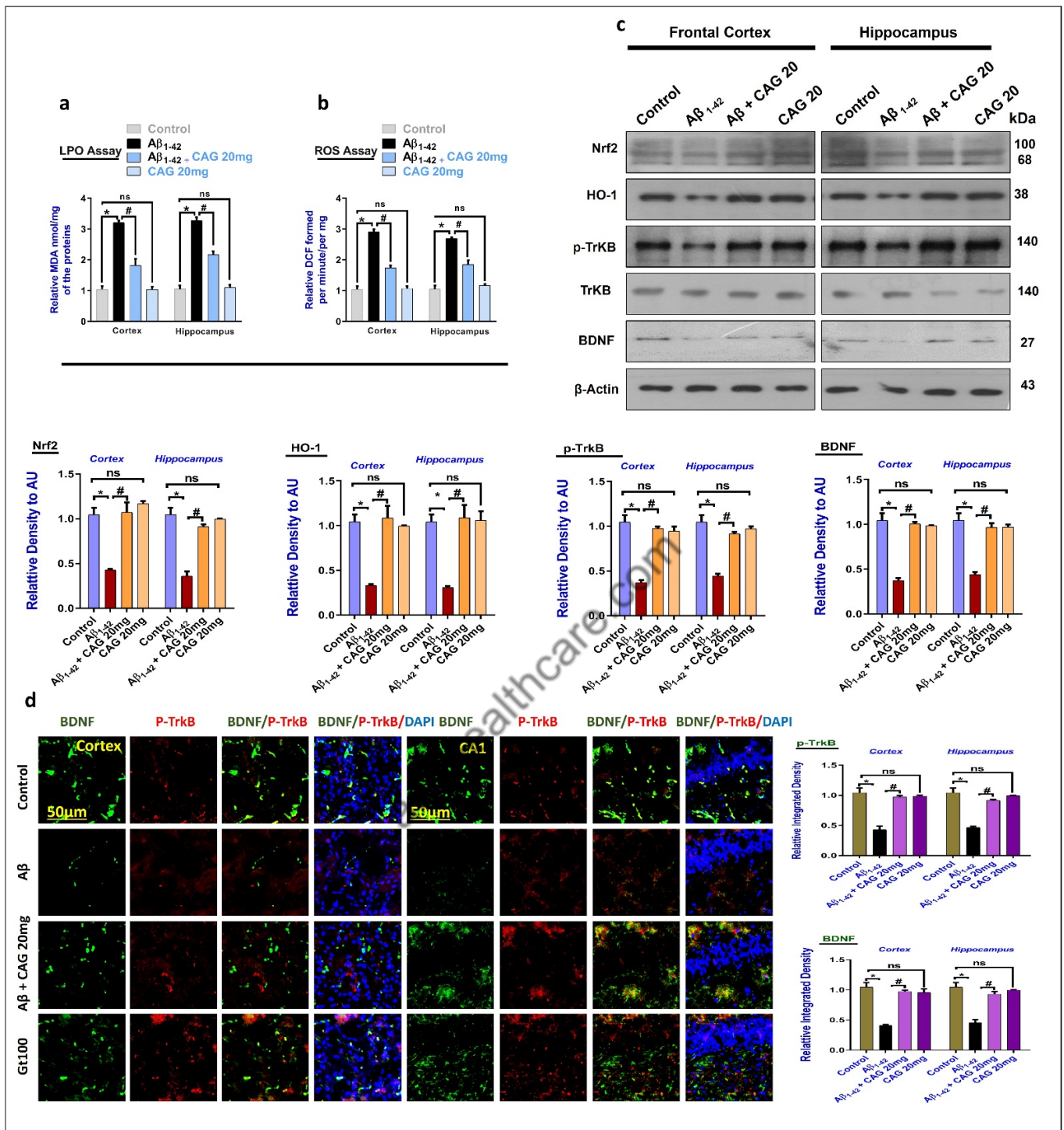
ously [44]. Our results showed elevated expression of LPO and ROS in the cortex and hippocampus compared to the control group. Interestingly, the level of ROS and LPO were significantly reduced in the cycloastragenol treated mice brain (Figure 1a,b). Next, we checked the expression of master anti-oxidant regulators, Nrf2, and its downstream target (HO-1) in the experimental groups. According to the Western blotting results, A $\beta$  markedly reduced the expression of Nrf2 and HO-1 compared to the saline-injected control group. These markers were significantly upregulated with the administration of Cycloastragenol. Next, we checked the expressions of BDNF and its associated receptor p-TrkB in the experimental mice brain. The results indicated reduced levels of BDNF and p-TrkB in the A $\beta$ -injected mice brain, compared to the saline-injected control mice. These markers were significantly enhanced in the A $\beta$  + Cycloastragenol co-treated mice brains (Figure 1c). The Western blot results were further strengthened with immunofluorescence analyses, which showed reduced expression of BDNF and p-TrkB in the A $\beta$ -treated mice brains (frontal cortex and hippocampus), compared to the control group. The reduced expressions of p-TrkB and BDNF were significantly restored in the A $\beta$  + Cycloastragenol co-treated mice compared to the A $\beta$ -injected mice (Figure 1d). Collectively, the Western blot and immunofluorescence results suggest that cycloastragenol has a regulating effect against the BDNF and its receptor in the A $\beta$ -induced AD mouse model.

### 3.2. Effects of Cycloastragenol against the cAMP Response Element-Binding Protein (CREB) and NeuN in the A $\beta$ -Injected Mice Brains

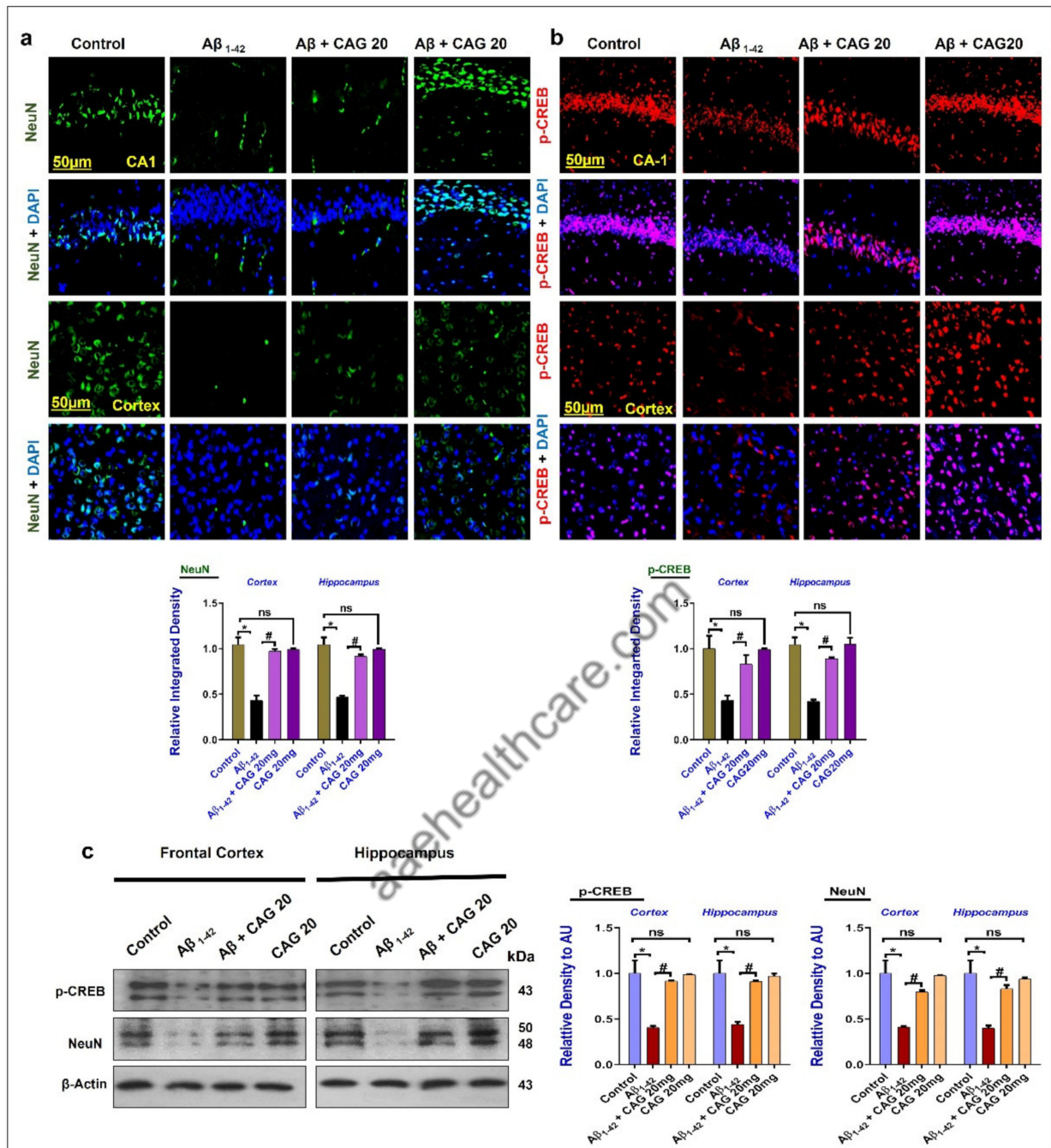
To further confirm the neuronal survival effects of cycloastragenol, we checked the expression of p-CREB and NeuN in the frontal cortex and hippocampus of the experimental mice brain. According to the immunofluorescence analysis, the expressions of NeuN and p-CREB were significantly reduced in the A $\beta$ -injected mice brain compared to the saline-injected control group. These markers were enhanced in the A $\beta$  + Cycloastragenol co-treated mice brain compared to the A $\beta$ -injected mice (Figure 2a,b). Furthermore, we conducted Western blotting for the expression of p-CREB and NeuN in the frontal cortex and hippocampus of the experimental mice's brains, which showed a reduced expression of these markers in the A $\beta$ -injected mice brains. As expected, these markers were upregulated in the A $\beta$  + Cycloastragenol co-treated group (Figure 2c).

### 3.3. Effects of Cycloastragenol against the Mitogen-Activated Protein (MAP) Kinases, Activated Astrocytes and Microglia, and Inflammatory Cytokines in the A $\beta$ -Injected Mice's Brains

To evaluate the effects of cycloastragenol against neuroinflammation-related intracellular signaling markers, we checked the expressions of MAP kinases, such as p-ERK, p-38, and p-JNK in the experimental mice brains. The findings showed an enhanced expression of p-JNK and p-38 and a reduced expression of p-ERK. These markers were significantly reversed with the administration of cycloastragenol. We have also checked the expression of activated Iba-1, GFAP, TNF- $\alpha$ , and IL-1 $\beta$  in the experimental mice brains. The finding showed that cycloastragenol reduced the expression of inflammatory cytokines in the A $\beta$ -injected mice brain (Figure 3a). Furthermore, the immunofluorescence analysis of p-JNK and p-38 also showed enhanced fluorescence of p-JNK and p-38 in the A $\beta$ -injected mice brain, which were significantly reduced in the A $\beta$  + Cycloastragenol co-treated mice (Figure 3b,c). The regulating effects of cycloastragenol against the MAP kinases suggest that cycloastragenol may protect the mice brain against AD-related intracellular signaling in the mice brain.

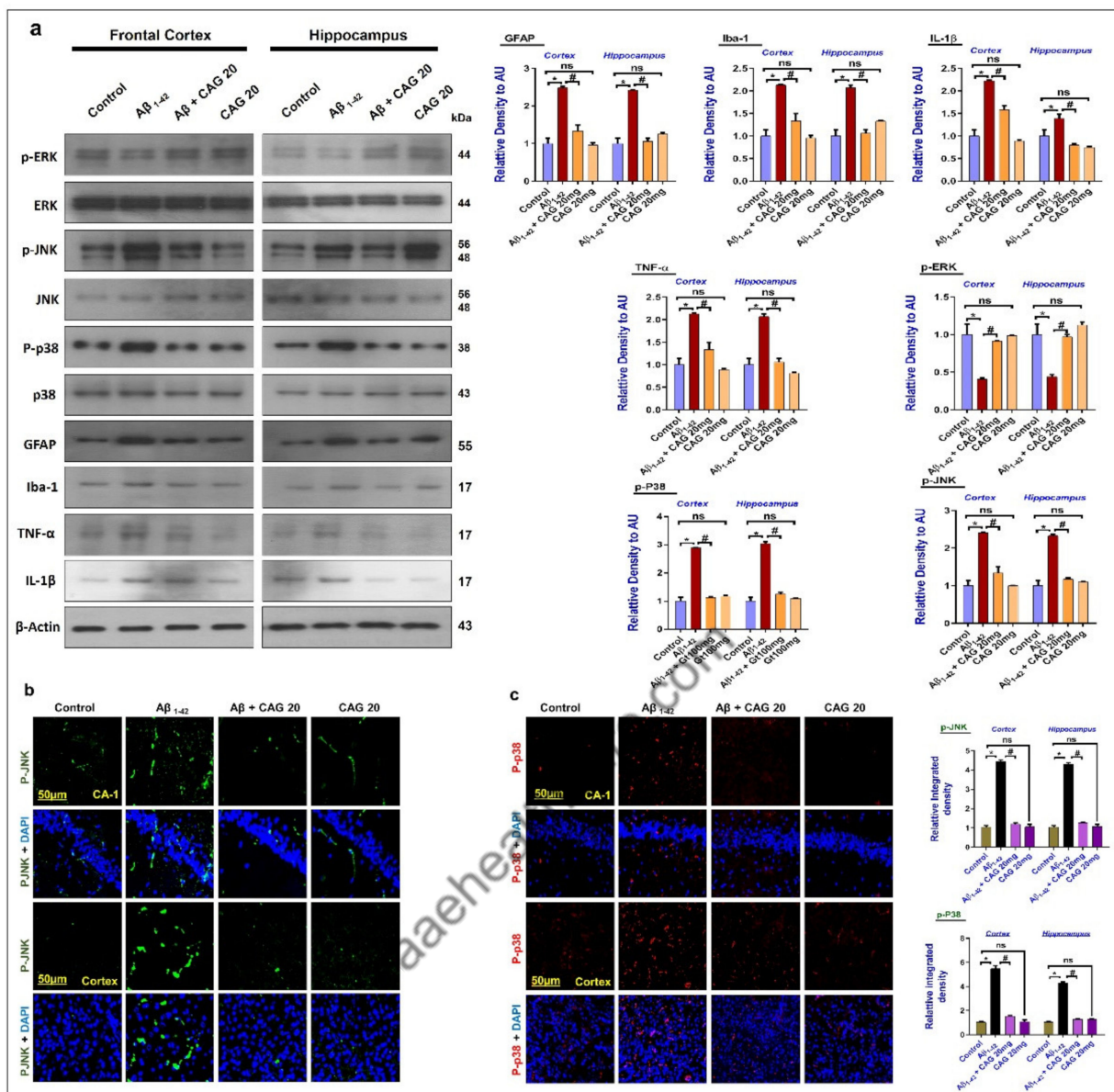


**Figure 1.** Effects of cycloastragenol against the elevated oxidative stress and altered expression of BDNF and p-TrkB in the Aβ-injected mice. (a,b) Graphical representation of LPO and ROS assays in vivo. (c) Western blot results of Nrf2, HO-1, p-TrkB, TrkB, and BDNF in the frontal cortex and hippocampus of the experimental mice, with respective bar graphs. (d) Immunofluorescence of BDNF and TrkB in the frontal cortex and hippocampus (CA1) of the experimental mice brain. The scale bar is 50 μm, green is BDNF, red is p-TrkB, and blue is DAPI for nuclear staining. The *p*-value <0.05 was considered a significant difference. \* showing a significantly different from the control group; # significantly different from the Aβ-injected group. Significant difference = \* *p* < 0.05; # *p* < 0.05. CAG20: Cycloastragenol 20 mg/kg, DAPI: 4',6-diamidino-2-phenylindole, Aβ: Amyloid beta, CAG: Cycloastragenol, ns: non-significant difference.



**Figure 2.** Effects of cycloastragenol against the reduced expressions of p-CREB and NeuN in the experimental mice's brains. (a,b) Immunofluorescence analyses of NeuN and p-CREB in the cortex and hippocampus of the experimental mice. Scale bar 50, the green NeuN and blue is DAPI (for visualizing the nucleus). (c) Western blot results of p-CREB and NeuN in the cortex and hippocampus of the experimental mice. The  $p$ -value  $< 0.05$  was considered a significant difference. \* showing a significantly different from the control group; # significantly different from the A $\beta$ -injected group. Significant difference = \*  $p < 0.05$ ; #  $p < 0.05$ . CAG 20: Cycloastragenol 20 mg/kg, DAPI: 4',6-diamidino-2-phenylindole, A $\beta$ : Amyloid beta, CAG: Cycloastragenol, ns: non-significant difference.



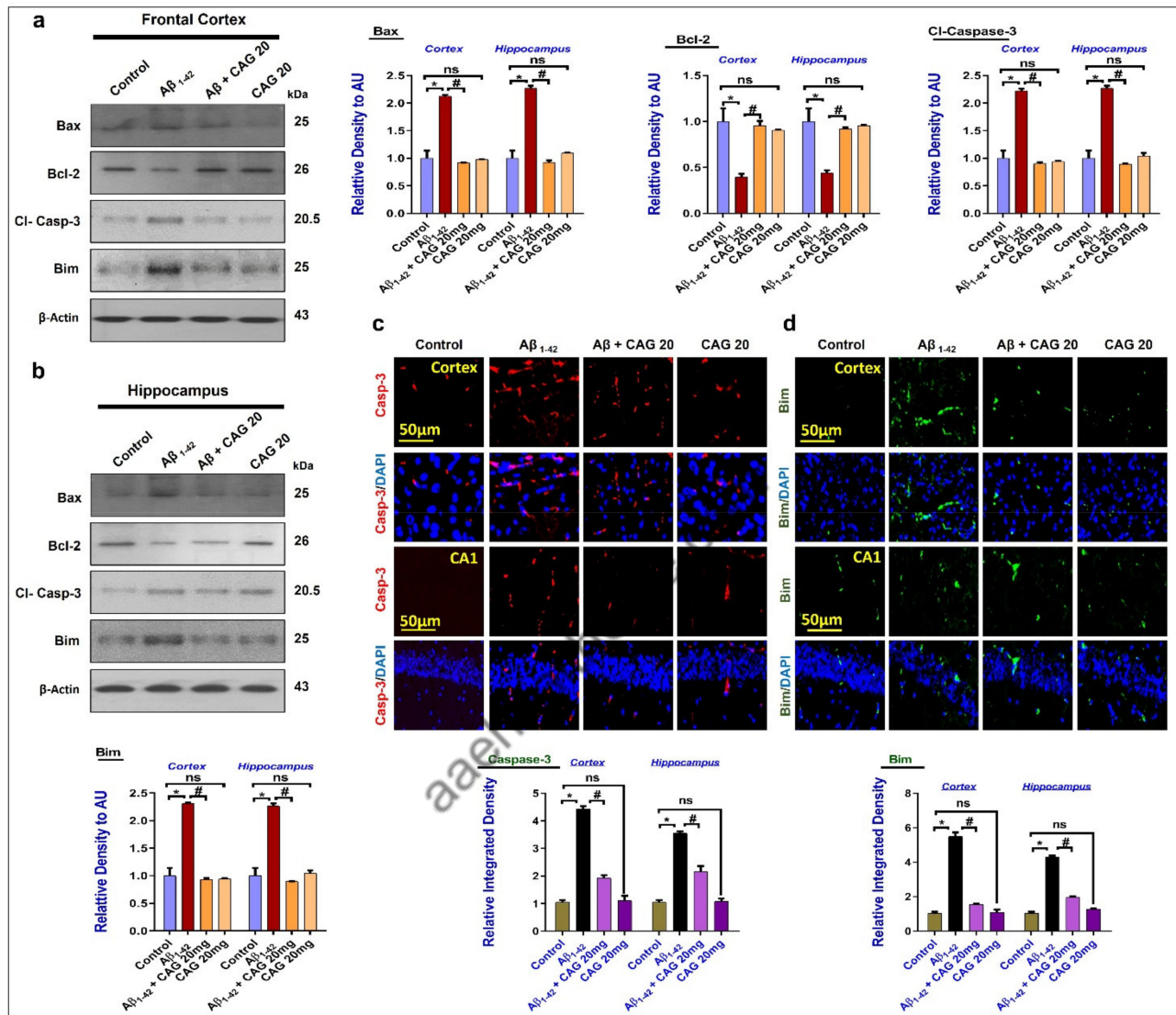


**Figure 3.** Effects of cycloastragenol against the Aβ-induced activated MAP kinases, and the inflammatory cytokines. (a) Western blot results of p-ERK, p-JNK, p-p38, GFAP, Iba-1, TNF-α, and IL-1β in the frontal cortex and hippocampus of experimental mice’s brains, with respective bar graphs. (b,c) Immunofluorescence analysis of p-JNK and p-p38 in the frontal cortex and hippocampus of experimental mice, scale bar is 50 μm. In panel-1 b,c, green is Aβ, red is p-P38 and blue is DAPI. The p-value < 0.05 was considered a significant difference. \* showing a significantly different from the control group; # significantly different from the Aβ-injected group. Significant difference = \* p < 0.05; # p < 0.05. CAG20: Cycloastragenol 20 mg/kg, DAPI: 4',6-diamidino-2-phenylindole, Aβ: Amyloid beta, CAG: Cycloastragenol, ns: non-significant difference.

### 3.4. Effects of Cycloastragenol against Aβ-Induced Apoptotic Cell Death

Apoptotic cell death has been a major player of neurodegeneration, which is regulated by the pro-apoptotic factor Bax and anti-apoptotic Bcl-2 [45]. To analyze the effects of cycloastragenol against Aβ-induced apoptotic cell death, we performed Western blot for Bax, Bcl-2, Casp-3, and Bim in the experimental groups, which showed that there was a significant upregulation in the expressions of pro-apoptotic proteins (Bax, Casp-3, and Bim) and a reduction in the level of anti-apoptotic proteins (Bcl-2) in the Aβ-treated mice brains (frontal cortex and hippocampus). The pro-apoptotic effects were significantly reduced with the administration of cycloastragenol (Figure 4a,b). The Western blot results

were further confirmed with the immunofluorescence analyses, which showed significant regulation of pro-apoptotic markers (Bim and Caspase-3) in the A $\beta$  + Cycloastragenol co-treated mice brains, compared to the A $\beta$ -injected group, showing the anti-apoptotic effects of cycloastragenol (Figure 4c,d).

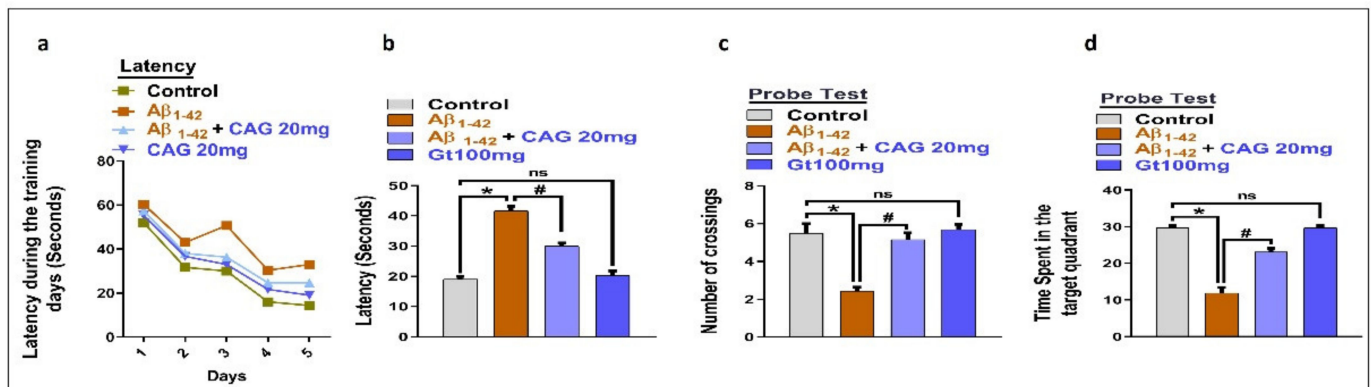


**Figure 4.** Effects of cycloastragenol against the mitochondrial dysfunction in an A $\beta$ -induced mouse model of Alzheimer's disease. (a,b) Western blot results of Bax, Bcl-2, cleaved Caspase-3, and Bim in the experimental mice's brains, with respective bar graphs. (c,d) Immunofluorescence analysis of Caspase-3 and Bim in the cortex and hippocampus of experimental mice, with respective bar graphs. The  $p$ -value  $< 0.05$  was considered a significant difference. \* showing a significantly different from the control group; # significantly different from the A $\beta$ -injected group. Significance = \*  $p < 0.05$ ; #  $p < 0.05$ . CAG 20: Cycloastragenol 20 mg/Kg, A $\beta$ : Amyloid beta, DAPI: 4',6-Diamidino-2-phenylindole, CAG: Cycloastragenol, ns: non-significant difference.

### 3.5. Effects of Cycloastragenol against A $\beta$ -Induced Memory Impairment

To analyze the effects of cycloastragenol against cognitive dysfunction, we performed the MWM test. According to our findings, the injection of A $\beta$  enhanced the latency to reach the platform, which was partially reduced with the administration of cycloastragenol (Figure 5a,b). Similarly, we checked the time spent in the target quadrant and the number of crossings of the platform in the probe test, which showed that cycloastragenol signifi-

cantly improved the time spent in the target quadrant and number of platforms crossings compared to the A $\beta$ -injected mice (Figure 5c,d).



**Figure 5.** Effects of cycloastragenol against memory dysfunction in A $\beta$ -injected mice. (a) Graph showing the latency to reach the platform during the training days. (b) Latency on day 6 after the completion of training. (c) Probe test, number of crossings of the platform. (d) Time spent in the target quadrant. The  $p$ -value  $< 0.05$  was considered a significant difference. \* showing a significant difference from the control group; # significantly different from the A $\beta$ -injected group. Significance = \*  $p < 0.05$ ; #  $p < 0.05$ . CAG 20: Cycloastragenol 20 mg/kg, A $\beta$ : Amyloid beta, CAG: cycloastragenol, ns: non-significant difference.

#### 4. Discussion

The current study has been conducted on the role of cycloastragenol against A $\beta$ -induced oxidative stress, neurogenic dysfunction, neuroinflammation, and apoptotic cell death. To unveil these effects, an A $\beta$ -induced mouse model was developed, and cycloastragenol was orally administered for 6 weeks. The collective findings indicated that the administration of cycloastragenol is effective in regulating oxidative stress, as shown by the reduced expression of LPO and ROS, and it enhanced the expression of Nrf2 and neurogenic processes, modulating the MAP kinases-mediated neuroinflammation, apoptotic cell death, and cognitive impairment.

Here, we have targeted the main etiological factors: oxidative stress, neurotrophic factors, MAP kinases, mitochondrial apoptosis, and memory impairment. For years, attempts have been made to explore the underlying pathogenic factors in the progression of neurodegenerative diseases; one of the key factors responsible for the neurodegeneration is elevated oxidative stress, which is characterized by increased lipid peroxidation, elevation in the levels of reactive oxygen species, and disruption in the levels of master antioxidant regulators, such as Nrf2 and HO-1 [46]. In addition, down-regulation in the expression of Nrf2 may affect the normal neurogenic process [47] and neuroinflammation [48]. The down-regulation in the expression of Nrf2 and HO-1 in the A $\beta$ -injected mice brain is per the previous studies conducted on the expression of Nrf2 in the AD-mouse models [2]. Boosting of the Nrf2 with the administration of specific agonists of Nrf2 or natural drugs has shown rescuing effects against neurodegeneration [39].

Another main factor is neurogenesis, which is suppressed with aging and in neurodegenerative conditions [49], and activation of the neurotrophic factors has rescued the brain against neurodegeneration [50]. As expected, cycloastragenol significantly enhanced the expression of BDNF and its associated receptor (p-TrkB) in the A $\beta$ -injected mice brains. The effects of cycloastragenol against the reduced expression BDNF and p-TrkB gives the clue that cycloastragenol may abrogate the neurogenic process by suppressing oxidative stress-related markers. The direct link between cycloastragenol and neurogenesis is still not clear, but it is suggested that Nrf2 may be involved in this process, as previous studies have suggested that the boosting of Nrf2 may enhance the neurogenic processes [51]. Here, we noted significant suppression in the expression of LPO and ROS; similarly, the expression of Nrf2 and HO-1 was significantly enhanced with the administration of cycloastragenol.

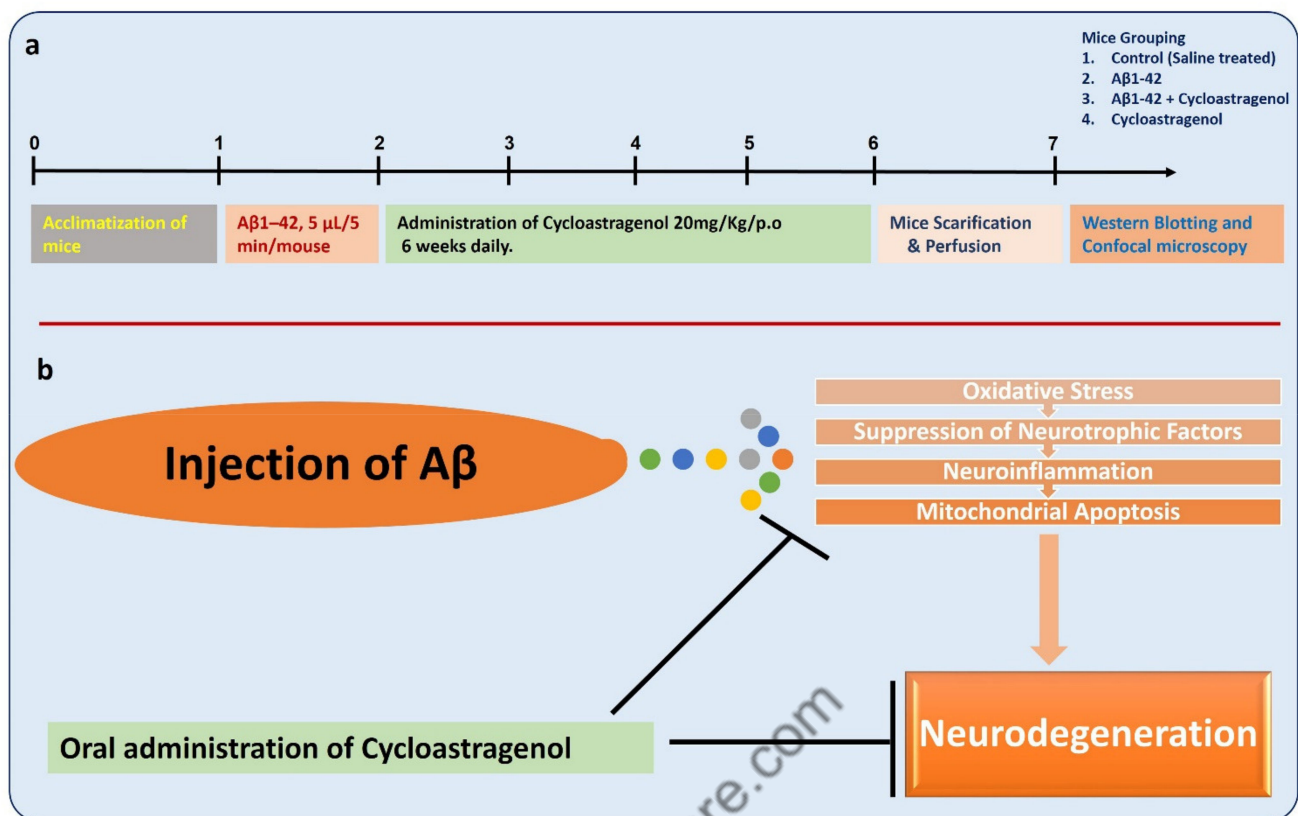
Similarly, the expression of neurogenesis-related factors was significantly restored with the administration of cycloastragenol. The antioxidant and neurogenic effects of cycloastragenol are per the previous studies [52,53]. Moreover, it has been suggested that boosting the neurotrophic factor may favor the neuronal functions and rescue the brains against neurodegeneration [54]. Neurotrophic factors are essential proteins, performing several physiological functions in the central and peripheral systems, maintaining the overall development, survival, and maintenance of the body [55]. The neurotrophins acts as growth factors, which are known for their ability to modulate several physiological functions. BDNF is a known factor that elicits its physiological functions by binding to its tyrosine receptor kinase-B (TrkB) receptor [56]. Here in our findings, there was a significant suppression in the expression of BDNF and p-TrkB in A $\beta$ -injected mice brains. The suppression of neurotrophic factors in the A $\beta$ -injected mice brains is per the previous studies [57]. As expected, the administration of cycloastragenol restored the level of p-TrkB, and BDNF in the A $\beta$ -injected mice brains (Figure 1). The CREB is a key regulator of neuronal maturation and differentiation in the adult hippocampal neurogenesis, and its activation leads to the transcription of memory-related genes, acting as a hub of mechanisms activated during the synaptic strengthening and memory processing. Restoration of the phosphorylation of CREB in A $\beta$ -induced mice with the administration of cycloastragenol suggests that the BDNF/p-TrkB/CREB pathway may be involved in the protective effects of cycloastragenol against A $\beta$ -induced neuroinflammation and apoptotic cell death. The activation of p-CREB and BDNF may rescue the neuronal cells against the A $\beta$ -induced neurodegeneration [58], as suggested by the enhanced expression of NeuN [59].

Elevated oxidative stress activates several intracellular signaling, including mitogen-activated protein kinases (MAPKs) [60], as the MAPKs play a major role in converting the extracellular stimuli into a range of effects, including cell proliferation, growth, and apoptosis [61]. The JNK and p38 MAPK are upregulated in response to various stressors [62]. As the vital genes in neuronal survival and death, we evaluated the expression of MAPKs, which showed that the expression of MAP kinases was significantly restored with the administration of cycloastragenol compared to the A $\beta$ -injected mice. The effects of cycloastragenol against A $\beta$ -induced activated MAP kinases may be partly due to enhancing the expression of Nrf2, as it was suggested previously that the boosting of Nrf2 may suppress p-JNK in neurodegenerative conditions [63].

Next, we checked the expression of apoptosis-related factors, as it has been suggested that elevated oxidative stress is responsible for the execution of mitochondrial apoptosis. Our findings showed that cycloastragenol reduced apoptosis and memory impairment in the A $\beta$ -injected mice brains. The neuroprotective and anti-apoptotic effects of cycloastragenol is per the previous studies conducted on astragenol [30]. The overall findings are suggesting that cycloastragenol may rescue the mice brains against AD-like pathological changes by decreasing the oxidative insult, enhancing brain neurotrophic factors, regulating MAP kinases, and reducing mitochondrial apoptosis and cognitive impairments.

## 5. Conclusions

Conclusively, the current findings strongly support the notion that cycloastragenol may reduce AD-related neurodegeneration by suppressing oxidative stress, neurotrophic factors, MAP kinases, and apoptosis-related markers, overall supporting the previous studies conducted on the role of cycloastragenol in AD-related conditions [36,64]. This shows the candidacy of cycloastragenol as a promising drug against AD-related neurodegenerative diseases. However, more mechanistic work is warranted to unveil the exact mechanisms involved in the neuroprotective effects of cycloastragenol. The overall study design and graphical abstract has been given here in Figure 6.



**Figure 6.** Study design and the graphical abstract. (a) Study design, showing the complete designing and regimen of the study, including mice's treatment, grouping, doses, and experimentation. (b) Graphical abstract, a simple sketch showing the protective effects of cycloastragenol against the suppressed neurotrophic factors, activated MAP kinases, and the mitochondrial dysfunction in A $\beta$ -injected mice.

**Author Contributions:** M.I., M.H.J. and K.C. designed the study, treated the mice, conducted the experiments, and wrote the manuscript, A.K., S.A., K.S. and M.W.K. conducted the experiments and helped in writing the manuscript. M.O.K. supplied all of the chemicals, supervised the study, provided all sorts of technical support, and critically reviewed the manuscript. All authors have read and agreed to the current version of the manuscript.

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