

A comparative study of the antioxidant activities of three series of first-and second-generation PPI dendrimers (G1 and G2) functionalized by 2-hydroxy-P-naphthoquinone

El Hadji Gorgui DIOUF¹, Talibouya NDIOR¹, Lahat NIANG², Mamadou Kébé¹, Mamadou Latyr Ndour¹, Adama Faye¹, Ibrahima BA¹, Nicolas Cyrille AYEISSOU² and Moussoukoye DIOF¹

¹Department of Chemistry, Faculty of Science and Technology, Cheikh Anta Diop University of Dakar, Dakar, Senegal

²Laboratory of Water, Energy, Environment and Industrial Processes (LE3PI) of the Higher Polytechnic School Dakar, Senegal

ABSTRACT

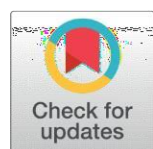
The work presented focuses on the synthesis of molecules capable of blocking the deleterious effects of oxidative stress. Oxidative stress is caused by an imbalance between the pro-oxidant and antioxidant systems, with the former benefiting. It is implicated in numerous pathologies, either as a cause or a consequence. Oxidative stress is involved in chronic processes such as atherosclerosis and diabetes. The work presented in this article focuses firstly on the synthesis of a new class of first- and second-generation PPI (Polypropylene Imine) dendrimers (G1 and G2) functionalized with 2-hydroxy-p-naphthoquinone, and secondly on the assessment of their antioxidant activity.

A study of antioxidant activity using the 1,1-diphenyl-2-picryl-hydrazyl (DPPH) method revealed that the dendrimers synthesized have antioxidant activity. All the results obtained were interesting.

Keywords Dendrimers, 2-hydroxy-p-naphthoquinone, Antioxidant, DPPH, PPI

INTRODUCTION

Oxidative stress is caused by a high and continuous production of reactive oxygen species (ROS) combined with an antioxidant response by the body¹. It damages biomolecules such as lipids, proteins and nucleic acids. Oxidative stress is the cause of a number of pathologies, including asthma, cancer, cardiovascular disease, diabetes, inflammatory diseases, liver disease and degenerative diseases.²



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Corresponding Author

El Hadji Gorgui DIOUF

<mailto:elhadjigorgui1.diouf@ucad.edu.sn>

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Under normal circumstances, the body establishes a balance known as the antioxidant-prooxidant balance by regulating the adaptive defense system.³ . To protect itself, the body sets up an antioxidant defense system. Antioxidants are substances that reduce or inhibit oxidative stress⁴ .

As a result, many researchers have turned their attention to antioxidants to find solutions to the problems caused by oxidative stress. Natural antioxidants play an important role in this research. Molecules are isolated and characterized from plants. Among the compounds studied, polyphenols (flavonoids, tannins, flavones, coumarins, etc.) play an important role.
5 6 7 8 9

Research has been carried out into the synthesis of new antioxidants that are effective against diseases linked to free radicals. Synthetic molecules include a new α -aminophosphonic acid

Obtained by Madi Djelloul (2023)¹⁰ . The biosynthesis and evaluation of the antioxidant activity of CuO nanoparticles was studied by Gharnout Ghizlane (2023)¹¹ .

In this context, the work presented in this article involves a comparative study of the antioxidant activities of three series of first-and second-generation PPI dendrimers (G1 and G2) functionalized with 2-hydroxy-p-naphthoquinone. The dendrimers were synthesized using the 'one pot' method of the modified Manich reaction.

Generally speaking, dendrimers refer to a family of polymers with a tree-like, three-dimensional, perfectly structured, monodisperse architecture.¹² and hyperbranched¹³ .

These are original, innovative molecules whose chemistry has been booming for years. Dendrimers have been evaluated for various biomedical applications, in particular as contrast agents in medical imaging or as drugs.¹⁴ .

Dendrimers have antiviral, antibacterial and antitumor properties. These molecules can be used to develop new organic/inorganic materials with controlled structures¹³ but also to modify, on a nanometric scale, the surface of existing materials¹⁵ .

The Lawson used in the synthesis of dendrimers is a derivative of para-naphthoquinone (p-NQ) substituted in position 2 by a hydroxyl group (OH). It is a compound in the quinone family. Individually, it has biological activity, particularly antifungal activity. It can be found in the branches and leaves of Lawsonia inermis and Lawsonia alba.

The molecular structures of naphthoquinones give them redox properties, making them active in a number of oxidative biological processes. They are found in various plant families, confirming the antioxidant power of naphthoquinones.

They have been used in traditional medicine by indigenous Amerindian populations for the treatment of a number of diseases, such as cancer.^{16 17} .

Based on reports from the study carried out by Dr Gonçalves de Lima in Recife (Pernambuco, Brazil)^{18 19} and his team on the microbicidal activity of naphthoquinones, other biological activities were found. Today, naphthoquinones are used in a number of areas,

Particularly in medicine.

In this article, the antioxidant activity of the molecules synthesized was assessed using DPPH (1,1-diphenyl-2-picryl-hydrazyl) as the reducing agent.

MATERIALS AND METHODS

Hardware

PPI G1-G5 dendrimers were purchased from SyMO-Chem B. V/University of Heindoven (The Netherlands). NMR spectra of the compounds were recorded at 400 MHz for the proton¹ H and at 75.5 MHz for¹³ C on a BRUKER AM 400 WB high-field spectrometer at the Western Regional Centre for Physical Measurements (CRMPO) at the University of Rennes 1. The antioxidant activity of the synthesized compounds was assessed using a control absorbance UV spectrophotometer (SPECORD 200 PLUS) (0.3 mL DPPH and 2.7 mL methanol) at the Electrochemistry and Membrane Processes Laboratory (LEPM), Higher Polytechnic School of Cheikh Anta Diop University of Dakar (Senegal).

General procedure of the synthesis

In a 150 mL Erlenmeyer flask protected from light, a solution of the appropriate Dendr-(NH)₂n in 10 mL of absolute ethanol was added to a suspension of 4-hydroxynaphthoquinone in 20 mL of absolute ethanol with magnetic stirring at room temperature. The gradual disappearance of the suspended solid observed was marked by the formation of a white solution. To ensure complete formation, the solution was left to stir for 15 minutes. The aldehyde in question was then added using a syringe (acetaldehyde for compounds 1a and 2 and benzaldehyde for compound 1b).

The resulting reaction mixture is then left under magnetic stirring at room temperature for 12 hours in the dark.

The precipitate formed was wrung out, washed with ethanol (2 times) and then with petroleum ether (2 times) before being dried in a thermostatic oven at 45°C for 1 hour.

Compounds 1a, 1b, and 2 were prepared according to the reaction scheme below:

-CHARACTERISATION OF COMPOUND 1A

- IR (KBr) /cm⁻¹_{max} : 3426 (ν_{O-H}) ; 3066 (ν_{C-H}) ; 2954 (ν_{C-H}) ; 2818 (ν_{C-H}) ; 1680 (ν_{C=O}) ; 1590 (ν_{C=C}) ; 1536 (δ_{N-H}) ; 1278 (ν_{C-O})

- NMR ¹ H (DMSO-d₆ , 400 MHz): δ(ppm) 16.80 (br. s, OH); 8.95 (s, NH); 7.90 (d, J³HH

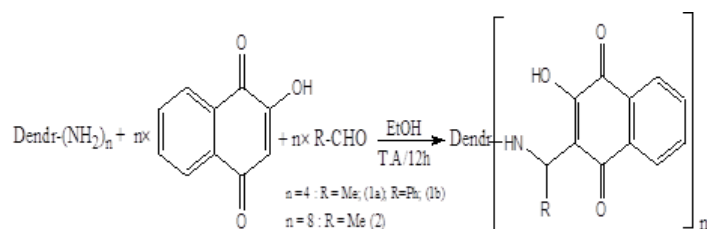


Figure 1 1: General equation for obtaining compounds 1a, 1b and 2

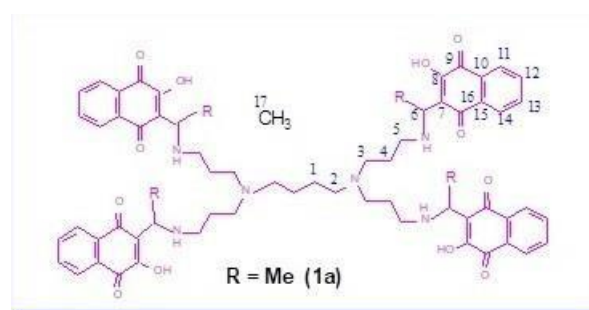


Figure 2 Structure of compound 1a

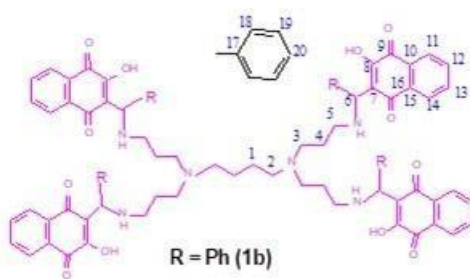


Figure 3 Structure of compound 1b

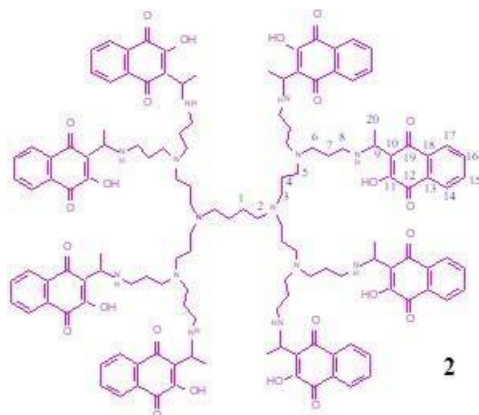


Figure 4 Structure of compound 2

= 6.8 Hz, H^{11} -Napht, 4H); 7.83 (d, $J^{3HH} = 6.4$ Hz, H^{14} -Napht, 4H); 7.68 (t, $J^{3HH} = 7.6$ Hz, H^{12} -Napht, 4H); 7.56 (t, $J^{3HH} = 7.2$ Hz, H^{13} -Napht, 4H); 4.56 (q, $J^{3HH} = 4.4$ Hz, H^6 , 4H); 2.81 (s, H^5 , 8H); 2.40-1.95 (s [2.23 ppm (H^3 , 8H) + 2.14 ppm (H^2 , 4H)], 12H); 1.61 (s, H^4 , 8H); 1.43 (d, $J = 4.4$ Hz, H^{17} , 12H); 1.22 (s, H^1 , 4H).

- **NMR¹³ C (DMSO-d₆, 75.5 MHz): δ (ppm)** 184.7 (d, $J = 28$ Hz, C=O); 178.9 (d, $J = 20$ Hz, C=O); 170.2 (t, $J = 64$ Hz, C-OH); 134.6 (d; C^{IV} -Napht); 133.7 (CH-Napht); 131.3 (C^{IV} -Napht); 130.8 (CH-Napht); 125.4 (CH-Napht); 125.1 (CH-Napht); 111.6 (C^7); 52.5 (s, C^2); 51.3 (s, C^6); 50.7 (s, C^3); 43.6 (d, C^5); 23.6 (C^1); 23.0 (C^4); 17.42 (s; C^{17}).

• **Mass (ESI/ CH₃ OH-CH₃ Cl-95:5).** m/z theoretical [found (uncertainty)] [**M-4H+3Na**]⁻ (C₆₄H₈₆N₁₂O₁₂ Na₃) 1181.45938 [1181.4594 (0 ppm)].

-CHARACTERISATION OF COMPOUND 1B

- **IR (KBr) /cm^v max-1** : 3424 (γ O-H) ; 3060 (γ C-H) ; 2950 (γ C-H) ; 1677 (γ C-H) ; 1679 (γ C=O) ; 1591 (γ C=C) ; 1522 (δ N-H) ; 1276 (). γ C-O

- **NMR¹ H (DMSO-d₆, 400 MHz): δ (ppm)** 16.50 (s, OH) ; 9.60 (s, NH) ; 7.88 (d, $J^{3HH} = 8$ Hz, H^{11} -Napht, 4H) ; 7.81 (d, $J^{3HH} = 7.6$ Hz, H^{14} -Napht, 4H); 7.66 (t, $J^{3HH} = 7.2$ Hz, H^{12} -Napht, 4H); 7.50-7.60 (m, H^{13} -Napht + H-Ph, 12H); 7.21-7.33 (m, H-Ph, 12H); 5.55 (s, H^6 , 4H); 2.91 (s, H^5 , 8H); 2.40-2.00 (s [2.28 ppm (H^3 , 8H) + 2.11 ppm (H^2 , 4H)], 12H); 1.69 (s, H^4 , 8H); 1.22 (s, H^1 , 4H).

- **¹³ C NMR (DMSO-d₆, 400 MHz): δ (ppm)** 184.5 (d, $J = 88$ Hz, C=O); 178.9 (d, $J = 84$

Hz, C=O); 170.0 (d, $J = 88$ Hz, C-OH); 138.4 (C^{IV} -Ph); 134.3 (d, C^{IV} -Naph); 133.6 (CH-Naph); 131.3 (C^{IV} -Naph); 130.9 (CH-Naph); 128.2 (CH-Ph); 127.7 (CH-Ph); 127.6 (CH-Ph); 125.3 (CH-Naph); 125.0 (CH-Naph); 111.2 (C^{IV} , C^3 -Naph); 58.7 (PhCHN); 52.2 (t; NCH₂ CH₂ CH₂ CH₂ N); 50.5 (d, NCH₂ CH₂ CH₂ NH); 44.7 (t, NCH₂ CH₂ CH₂ NH); 22.4 (s, NCH₂ CH₂ CH₂ CH₂ N); 23.5 (s, NCH₂ CH₂ CH₂ NH).

• **Mass (ESI/CH₃ OH-CH₃ Cl-95:5).** m/z theoretical [found (uncertainty)] [**M-H**]⁻ (C H N₈₄₇₉₆₁₂) O1363.57615 [1363.5758 (0 ppm)] ; [**M-2H+Na**]⁻ (C H N₈₄₇₈₆₁₂ ONa) 1385.55809 [1385.5564 (1 ppm)] ; [**M-3H+2Na**]⁻ (C H N₈₄₇₇₆₁₂ ONa₂) 1407.54004 [1407.5389 (1 ppm)]; [**M-4H+3Na**]⁻ (C H N₈₄₇₆₆₁₂ ONa₃) 1429.52198 [1429.5200 (1 ppm)].

-CHARACTERISATION OF COMPOUND 2

- **IR (KBr) /cm⁻¹ max-1** : 3412 (γO-H) ; 3066 (γC-H) ; 2954 (γC-H) ; 2823 (γC-H) ; 1679 (γC=O) ; 1591 (γC=C) ; 1522 (δN-H) ; 1277 (γC-O)

- **NMR¹ H (DMSO-d₆ , 400 MHz):** δ (ppm) 16.85 (s, OH); 8.97 (s, NH); 7.88 (s, H¹⁴ -Naph, 8H); 7.81 (s, H¹⁷ -Naph, 8H); 7.64 (d, $J^{HH} = 8$ Hz, H¹⁵ -Naph, 8H); 7.53 (s, H¹⁶ -Naph, 8H) ; 4.56 (s, H⁹, 8H); 2.79 (s, H⁸, 16H); 2.26 (s, H⁶ + H⁵ + H³ + H², 36H); 1.62 (H⁷, 16H); 1.43 (s, H²⁰, 24H); 1.23 (s, H⁴ + H¹, 12H).

- **NMR¹³ C (DMSO-d₆ , 400 MHz):** δ(ppm) 184.7 (s, C=O) ; 179.1 (s, C=O) ; 169.9 (t, $J = 64$ Hz, C-OH) ; 134.4 (d, C^{IV} -Naph) ; 133.6 (d, CH-Naph) ; 131.6 (CH-Naph) ; 131.2 (C^{IV} -Naph) ; 130.7 (CH-Naph) ; 125.3 (CH-Naph); 125.0 (CH-Naph); 111.6 (s, C¹⁰ - Naph); 51.3 (s, C⁹) ; 50.5 (s, NCH₂ CH₂ CH₂ NH); 43.8 (d, NCH₂ CH₂ CH₂ NH); 23.2 (s; NCH₂ CH₂ CH₂ NH); 17.47 (s, C).²⁰

• **Mass (ESI/CH₃ OH-CH₃ Cl-80 : 20).** m/z theoretical (found (uncertainty)) [**M-H**]⁻ (C H N₁₃₆₁₅₉₁₄₂₄) O2372.16572 (2372.1561 (4 ppm)).

ASSESSMENT OF ANTIOXIDANT ACTIVITY

2.3.1. Principle

The principle of this method is to use the violet-colored DPPH as a free radical scavenger. In the presence of an antioxidant (A-H), DPPH turns yellow. As the change in color is proportional to the antioxidant power of a substance, it can be monitored by UV-visible spectrometry by measuring the decrease in absorbance at 517 nm caused by the antioxidant.

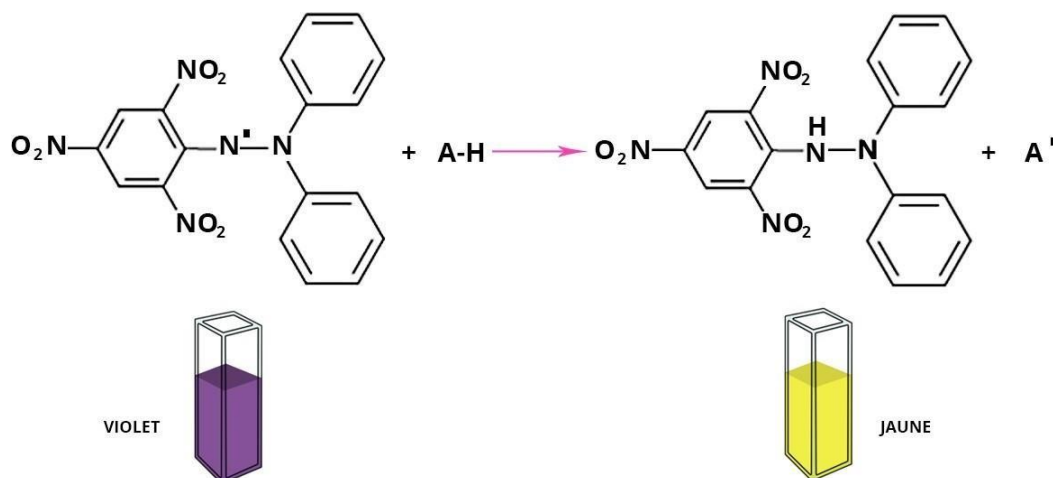


Figure 5 Modification of DPPH- during electronic transfer

EXPERIMENTAL PROTOCOL

The antioxidant activity of the compounds was assessed by monitoring the scavenging kinetics of the DPPH (1,1-diphenyl-2-picryl-hydrazyl) radical. Tests were carried out with 2,2- diphenyl-1-picrylhydrazyl (DPPH) using the method reported by Oliveira et al., [20] with some adjustments. A mass of 0.10 g of compounds (1a, 1b and 2) was dissolved in 25 mL of

Methanol to obtain a solution with a concentration of $4000 \mu\text{g. mL}^{-1}$. Thus, 2.7 mL of DPPH ($40 \mu\text{g. mL}^{-1}$) prepared in methanol was introduced into a test tube containing 0.3 mL of the solution. The mixture was stirred for five (5) minutes and then incubated in the dark at room temperature for 30 minutes. After this incubation period, the absorbance was read at 517 nm against a blank (0.3 mL of the solution and 2.7 mL of methanol) using a UV spectrophotometer (SPECORD 200 PLUS). The absorbance of the control (0.3 mL DPPH and 2.7 mL methanol) was determined at this wavelength. The free radical scavenging activity (FSA) is expressed as a percentage of DPPH reduced using the following equation:

$$AAR (\%) = 100 \times \left(\frac{\text{Absorbance}_{\text{Contrôle}} - \text{Absorbance}_{\text{échantillon}}}{\text{Absorbance}_{\text{Contrôle}}} \right)$$

RESULTS

The results of the real-life tests are presented in Table 1 as a percentage of DPPH trapping and plotted on a diagram for comparison.

Table 1: Percentage of DPPH reduced by compounds 1a, 1b

Samples	1a	1b	2
AAR (%)	23,237	2,441	5,244

DISCUSSION

The products were obtained using the synthesis method developed by Baramée et al., in 2006. However, the thermal conditions were modified for our synthesis, as revealed by Neves et al.²⁰.

Syntheses were carried out at room temperature and protected from light due to the degradation of the products after heating above 40°C. The order of introduction of the reagents was as follows: 2-hydroxy-p-naphthoquinone, then the dendrimer and finally the aldehyde.

The products obtained were isolated after precipitation, and purified by washing with ethanol and then petroleum ether. Yields of around 80% were obtained. The products were then

subjected to chemical characterization: NMR¹ H, NMR¹³ C {¹ H}, IR without any further purification operations.

The results obtained from the DPPH free radical absorbance test gave us the percentages of DPPH reduced by the three synthesized products listed in Table 1. In the light of these results, it can be seen that all the dendrimers synthesized have free radical scavenging capacity and that the values for the percentages of DPPH reduced are very different.

A comparison of the percentages of DPPH reduced shows that P 1b < P2 < P1a. All three products are synthesized on the basis of naphthoquinone. The only differences are in the generation or in the alkyl radical. 1b, the compound with the lowest antioxidant activity, is a first-generation dendrimer (G1) bearing a phenyl group as a radical. It is followed by compound 2, which is a second-generation dendrimer (G2) with eight methyl groups. This proves that the antioxidant character of the synthesized dendrimers is enhanced more by the methyl groups than by the phenyl groups. However, in the case of compound 2, the antioxidant activity seems to be attenuated by steric hindrance. This observation confirms that the antioxidant activity of the products depends in part on the methyl group and the environment of the dendrimer. For example, 3,3',5,5'-tetra-*t*-butyl-diphenyl-4,4'-diol showed a protective effect against free radical attack and a protective effect on neuronal cells²¹. This synthetic product has twelve methyl groups in its structure. It is therefore highly likely that its significant antioxidant activity is due in part to the hydroxyl groups, the conjugation of the π in the two benzene rings, but also to the presence of methyl groups. Regarding flavonoids, their antioxidant power can be improved by a few structural factors such as: the number of OH groups available, the C2-C3 double bond and a single OH in the 4' position, a catechol function on the B ring, the presence of C4'-OH and methylation, which has

variable effects²¹. The effect of steric hindrance is felt in dendrimer 2. This is confirmed by comparing the activities of 1a (23.237%) and 2 (5.244%) with those of compounds 1a (23.237%), which is a first-generation dendrimer with four methyl groups, and 1b (2.441%), which has four phenyl groups and is of the same generation as 1a. Our results also show that the activity of the dendrimers synthesized does not depend on the number of hydroxyl (OH) groups in the molecule. For example, compound 1a has the same number of OH groups as 1b, even though their antioxidant activities are very different. This observation is more than valid in view of the results for compound 1a, which has four OH groups and a much higher antioxidant activity than compound 2, which has eight OH groups.

CONCLUSION

This work is devoted to the synthesis and evaluation of the antioxidant activity of new molecules, by developing conjugated PPI dendrimers, easily accessible by a "one pot" synthesis based on the Mannich reaction. Antioxidants make a significant contribution to disease prevention. This is why, in the pharmaceutical industry, the development of new methodologies for the synthesis and preparation of molecules for therapeutic use has been set as an objective and has become a preoccupation for researchers. It is in this context that three new molecules based on first (G1) and second (G2) generation PPI dendrimers functionalized by 2-hydroxy-p-naphthoquinone have been synthesized for antioxidant purposes.

L The actual structures of the molecules prepared are in line with those expected. They were confirmed by the usual characterization techniques: H NMR¹, C NMR¹³ and dept, infrared (IR) and mass spectrometry.

Assessment of antioxidant activity using the DPPH method* showed that the dendrimers synthesized (1a, 1b and 2) have very significant antioxidant power.

DECLARATIONS:

Authors' contributions:

Contributor Role	Degree of Contribution		
	Lead	Equal	Supporting
Conceptualization		TN	EGD
Data curation			
Formal analysis	CG	EGD	TN
Funding acquisition		EGD	TN
Investigation		AKD	TN, EGD
Methodology		AKD, CG	TN, EGD
Project administration	AF	MK, MLN	
Resources			
Software		AF; MK	MLN
Supervision		AKD	MD; EGD
Validation		AKD; EGD	MD
Visualization			
Writing-original draft		TN	EGD

Conflict of interest: None

Ethical Approvals: The research was conducted by ethical standards and guidelines, and any necessary approvals from institutional review boards or ethical committees were obtained.

Funding Resources: None

REFERENCES

1. Arenas P. Medicine and magic among the Maka indians of the Paraguayan Chaco. *Journal of Ethnopharmacology*. 1987;21(3):279—295. [https://doi.org/10.1016/0378-8741\(87\)90104-8](https://doi.org/10.1016/0378-8741(87)90104-8).
2. Bastien JW. Pharmacopeia of qollahuaya andeans. *Journal of Ethnopharmacology*. 1983;8(1):97—111. [https://doi.org/10.1016/0378-8741\(83\)90091-0](https://doi.org/10.1016/0378-8741(83)90091-0).
3. Docampo R, Moreno SNJ. Free Radical Metabolites in the Mode of Action of Chemotherapeutic Agents and Phagocytic Cells on *Trypanosoma cruzi*. *Reviews of Infectious Diseases*. Phytochemical study and evaluation of the biological activities of the resin of the genus *Pinus* sp. 1984;6(2):223—238. <https://doi.org/10.1093/clinids/6.2.223>.
4. Gottlieb OR, Mors WB. Potential utilization of Brazilian wood extractives. *J Agric Food Chem*. 1980;28(2):196—215. doi.org/10.1021/jf60228a023.
5. Wahls TL, A C, Snetselaar LG. Review of Two Popular Eating Plans within the Multiple Sclerosis Community: Low Saturated Fat and Modified Paleolithic. *Nutrients*. 2019;11(2):352. doi.org/10.3390/nu11020352.
6. Rochette L. Stress oxydant et sepsis. *Réanimation*. 2008;17(6). [https://doi.org/10.1016/S1624-0693\(08\)73932-X](https://doi.org/10.1016/S1624-0693(08)73932-X).
7. Wang Z. Biochemical study of mechanism of damage to the retinal pigment epithelium. Northern Illinois University ProQuest Dissertations Publishing. 2005;p. 202—225. Available from: <https://search.proquest.com/openview/4cd6e357352b348651042de54574791e/1?pq-origsite=gscholar&cbl=18750&diss=y>.
8. Favier A. Intérêt conceptuel et expérimental dans la compréhension des mécanismes des maladies et potentiel thérapeutique. l'actualité chimique; 2003. Available from: <https://new.societechimiquedefrance.fr/wp-content/uploads/2019/12/2003-nov-dec-269-18-Favier.pdf>.

9. Salem JH. Extraction, identification, caractérisation des activités biologiques de flavonoïdes de *Nitraria retusa* et synthèse de dérivés acylés de ces molécules par voie enzymatique. INSTITUT NATIONAL POLYTECHNIQUE DE LORRAINE.; 2009. Available from: <https://hal.science/tel-01748769/>.
10. Jacob L. L'insuffisance rénale aiguë. and others, editor. Springer Paris; 2007. <https://doi.org/10.1007/978-2-287-71152-7>.
11. Maurent K, Vanucci-Bacqué C, Baltas M, Nègre-Salvayre A, Augé N, Bedos-Belval F. Synthesis and biological evaluation of diarylheptanoids as potential antioxidant and anti-inflammatory agents. *European Journal of Medicinal Chemistry*. 2018;144(20):289—299. <https://doi.org/10.1016/j.ejmech.2017.12.033>.
12. Droillard MJ, Paulin A. Isozymes of Superoxide Dismutase in Mitochondria and Peroxisomes Isolated from Petals of Carnation (*Dianthus caryophyllus*) during Senescence. *Polymer Journal*. 1990;94(3):1187—1192. <https://doi.org/10.1104/pp.94.3.1187>.
13. M AC, Arisi ACM, Cornic G, Jouanin L, Foyer CH. Overexpression of Iron Superoxide Dismutase in Transformed Poplar Modifies the Regulation of Photosynthesis at Low CO₂ Partial Pressures or Following Exposure to the Prooxidant Herbicide Methyl Viologen. 1998;117(2):565—574. <https://doi.org/10.1104/pp.117.2.565>.
14. Yoshimoto M, Sakamoto H, Yoshimoto N, Kuboi R, Nakao K. Stabilization of quaternary structure and activity of bovine liver catalase through encapsulation in liposomes. *Enzyme and Microbial Technology*. 2007;41(6-7):849—858. <https://doi.org/10.1016/j.enzmtec.2007.07.008>.
15. Nicholls P. Classical catalase: Ancient and modern. *Archives of Biochemistry and Biophysics*. 2012;525(2):95—101. <https://doi.org/10.1016/j.abb.2012.01.015>.
16. Schmutz DJL. Photodermatologie. Photobiologie, photoprotection et photothérapie. 3rd ed. and others, editor; 2018. Available from: https://www.librairie medicale.com/fr/catalogue/doc/photodermatologie-3e-edition_1092/lm_ouvrage.dhtml.
17. Neves AP, Barbosa CC, Greco SJ, Greco SJ, Vargas MD, Visentin LC, et al. Novel aminonaphthoquinone mannich bases derived from lawsone and their copper(II) complexes: synthesis, characterization and antibacterial activity. *J Braz Chem Soc*. 2009;20(4):712. <https://doi.org/10.1590/S0103-50532009000400015>.
18. BOUBEKRI C. Etude de l'activité antioxydante des polyphénols extraits de *Solanum melongena* par des techniques électrochimiques. Université Mohamed Khider – Biskra; 2014. Available from: <http://thesis.univ-biskra.dz/id/eprint/62>.
19. a b WB, Sghaier MB, Kilani S, Bouhlef I, Dijoux-Franca MG, Ghedira K, et al. Evaluation of antioxidant and antigenotoxic activity of two flavonoids from *Rhamnus alaternus* L. (Rhamnaceae): Kaempferol 3-O- β -isorhamninoside and rhamnocitrin 3-O- β -isorhamninoside. *Food and Chemical Toxicology*. 2011;49(5):1167—1173. <https://doi.org/10.1016/j.fct.2011.02.011>.
20. Boubekri C. Study of the antioxidant activity of polyphenols extracted from *Solanum melongena* by electrochemical techniques. Université Mohamed Khider Biskra; 2014. Available from: <http://thesis.univ-biskra.dz/id/eprint/62>.

21. Bhourri W, Sghaier MB, Kilani S, Bouhlef I, Ghedir LC, Dijoux-Franca MG, et al. Evaluation of antioxidant and antigenotoxic activity of two flavonoids from *Rhamnus alaternus* L (Rhamnaceae): Kaempferol 3-O- β -isorhamninoside and rhamnocitrin 3-O- β -isorhamninoside. 2011;49(5):1167— 1173. <https://doi.org/10.1016/j.fct.2011.02.011>.