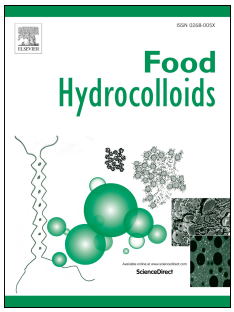
The colloidal stabilization of young red wine by Acacia senegal gum: The involvement of the protein backbone from the protein-rich arabinogalactan-proteins

Michael Nigen, Rafael Apolinar Valiente, Nerea Iturmendi, Pascale Williams, Thierry Doco, Virginie Moine, Arnaud Massot, Isabelle Jaouen, Christian Sanchez

Accepted Manuscript



The colloidal stabilization of young red wine by Acacia *senegal* gum: The involvement of the protein backbone from the protein-rich arabinogalactan-proteins

Michaël Nigen, Rafael Apolinar Valiente, Nerea Iturmendi, Pascale Williams, Thierry Doco, Virginie Moine, Arnaud Massot, Isabelle Jaouen, Christian Sanchez

PII: S0268-005X(19)30393-5

DOI: https://doi.org/10.1016/j.foodhyd.2019.105176

Article Number: 105176

Reference: FOOHYD 105176

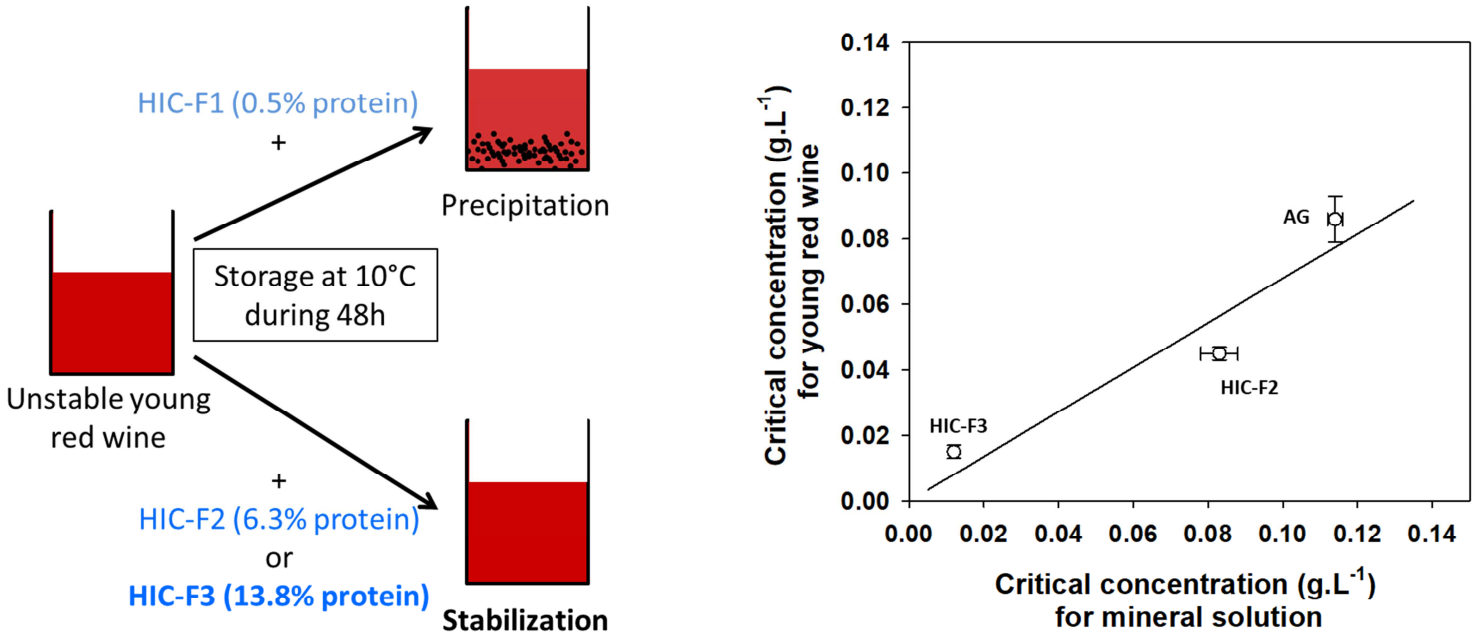
To appear in: *Food Hydrocolloids*

Received Date: 18 February 2019

Revised Date: 21 May 2019

Accepted Date: 18 June 2019

Please cite this article as: Nigen, Michaë., Valiente, R.A., Iturmendi, N., Williams, P., Doco, T., Moine, V., Massot, A., Jaouen, I., Sanchez, C., The colloidal stabilization of young red wine by Acacia *senegal* gum: The involvement of the protein backbone from the protein-rich arabinogalactan-proteins, *Food Hydrocolloids* (2019), doi: https://doi.org/10.1016/j.foodhyd.2019.105176.



Graphical Abstract.

The colloidal stabilization of young red wine by Acacia *senegal* gum: The involvement of the protein backbone from the protein-rich arabinogalactan-proteins

Michaël Nigen[a]*, Rafael Apolinar Valiente[a], Nerea Iturmendi[c], Pascale Williams[b], Thierry Doco[b], Virginie Moine[c], Arnaud Massot[c], Isabelle Jaouen[d] and Christian Sanchez[a]

[a] UMR1208 Ingénierie des Agropolymères et Technologies Emergentes, INRA-Montpellier SupAgro-CIRAD-Université Montpellier, 2 Place Pierre Viala F-34060 Montpellier, France

[b] UMR 1083 Science Pour l'Œnologie, INRA-Montpellier SupAgro-Université Montpellier, 2 Place Pierre Viala F-34060 Montpellier, France

[c] BIOLAFFORT, 126 quai de la Souys, 33100 Bordeaux, France

[d] ALLAND & ROBERT, 9 rue Saintonge, 75003 Paris, France

* corresponding author. Tel.: 33 4 99 61 26 15. Fax: 33 4 99 61 30 76. E-mail: michael.nigen@umontpellier.fr

Abstract

The arabinogalactan-proteins (AGPs) ~~type biopolymers~~ from Acacia *senegal* gum are used as protective colloid in young red wines to prevent the precipitation of the coloring matter. Usually, Acacia *senegal* gum is chosen based on its efficiency to stabilize iron hexacyanoferrate salts in hydro-alcoholic solution. In this study, the protective activity of Acacia *senegal* gum and its ~~three~~ macromolecular fractions (HIC-F1, HIC-F2 and HIC-F3), separated according to their hydrophobicity, towards the precipitation of iron hexacyanoferrate salts and polyphenols in hydro-alcoholic solutions are reported. ~~The~~ AGPs prevent the colloidal instability of both iron hexacyanoferrate salts and polyphenols in "model" hydro-alcoholic solutions and young red wine with a good correlation between results obtained on both systems. This result ~~then~~ strengthens the use of iron hexacyanoferrate salts (hydro-alcoholic – mineral test) for the evaluation of the protective activity of A. *senegal* gum in young red wine. The precipitation of iron hexacyanoferrate salts is avoided by the electrostatic binding of Ca^{2+}, the driver of the instability, with ~~the~~ negatively charged carried by amino-acids from the protein backbone or both by amino acids and uronic acid monosaccharides localized close to the protein backbone of AGPs. The protective activity closely depends on the protein content of AGPs in both iron hexacyanoferrate salts and polyphenols hydro-alcoholic solutions: the more they are rich in proteins, the more their colloidal stabilizing efficiency is (HIC-F3>HIC-F2>HIC-F1). The differences observed in the protective activity between AGPs from the three HIC fractions are relied not only to their protein content but also to their related rate of glycosylation that modulates the protein accessibility to its environment, then their physicochemical properties as their hydrophobic behavior.

Keywords: Acacia gum, Arabinogalactan proteins, colloidal stability, young red wine, coloring matter

1. Introduction

Red wine is a mixture of water, alcohols, organic acid and of complex molecules at the origin of its organoleptic properties and in constant evolution during ageing. The color as well as the clarity of red wines are ones of the qualities required by the consumers. Red wines must present a colloidal stability not only at the time of bottling but also during ageing and storage until its consumption (Ribéreau-Gayon, Glories, Maujean & Dubourbieu, 2006). The phenolic compounds, responsible of the organoleptic perceptions, are also unstable molecules able to aggregate and precipitate both in young and aged red wines (Ribéreau-Gayon et al., 2006; Alcade-Eon, Garcia-Estévez, Puente, Rivas-Gonzalo & Escribano-Bailon, 2014). Among others, the phenolic compounds can react with ferric iron to form soluble complexes that may then flocculate and precipitate during ageing (Ribéreau-Gayon et al., 2006). The colloidal stability in young red wines may be ensured by several techniques as a cold treatment, fining or addition of protective colloids such as carboxymethyl cellulose, metatartaric acid, mannoproteins and Acacia gum (Waters, Pellerin & Brillouet, 1994; Waters, Pellerin & Brillouet, 1994a; Dupin, Stockdale, Williams, Jones, Markides & Waters, 2000; Escot, Feuillat, Dulau & Charpentier, 2001; Riou, Vernhet, Doco & Moutounet, 2002; Riberau-Gayon et al., 2006; Poncet-Legrand, Doco, Williams & Vernhet, 2007; Pérez□Lamela, García□Falcón, Simal□Gándara & Orriols□Fernández, 2007; Gerbaud, Gabas, Blouin & Crachereau, 2010; Teissedre, 2012; Gordillo, Cejudo-Bastante, Rodríguez-Pulido, Jara-Palacios, Ramírez-Pérez, González-Miret & Heredia, 2014). The cold and fining treatments cause the precipitation of existing particles responsible of the turbidity as well as those potentially formed during ageing. Therefore, both treatments have a clarifying and a stabilizing action (Riberau-Gayon et al., 2006). In young red wine, Acacia gum is used as a

protective colloid in order to prevent or limit the aggregation and precipitation of unstable colloids as the coloring matter (Ribereau-Gayon et al., 2006; Teissedre, 2012). In particular, Acacia gum macromolecules bind to polyphenols by the involvement of both hydrogen bonding and hydrophobic interactions that prevents their interaction and aggregation with proteins (de Freitas, Carvalho & Mateus, 2003; Mateus, Carvalho, Luis & de Freitas, 2004; Soares, Gonçalves, Fernandes, Mateus & de Freitas, 2009; Soares, Mateus & de Freitas, 2012; Chung, Rojanasasithara, Mutilangi & McClements, 2016). Hence, Acacia gum is mainly used in young red wine for its colloidal stabilizing properties. It stabilizes young red wine but does not clarify it.

Acacia gum is a natural exudate obtained from the trunk and branches of *Acacia senegal* and *Acacia seyal* trees (Williams & Phillips, 2000). Acacia gum macromolecules are highly glycosylated hydroxyproline-rich arabinogalactan-proteins (AGPs) belonging to the glycoprotein superfamily (Akiyama, Eda & Kato, 1984). AGPs from Acacia gum are mainly composed by sugars (D-galactose, L-arabinose, L-rhamnose, D-glucuronic acid, and 4-O-methyl-D-glucuronic acid) with a small fraction of proteins and minerals (Idris, Williams & Phillips, 1998; Lopez-Torrez, Nigen, Williams, Doco & Sanchez, 2015). The sugars are organized into hyperbranched polysaccharide blocks covalently linked to the polypeptide backbone in serine- and hydroxyproline-rich domains (Lopez-Torrez et al., 2015). The highly branched polysaccharide structure is formed by main chains of 1,3-linked *β*-D-galactopyranose substituted by side chains in O-6 position. Units of α-L-arabinofuranosyl and α-L-rhamnopyranosyl are distributed in the main and side chains while β-D-glucuronopyranosyl and 4-O-methyl-β-D-glucuronopyranosyl are mostly end-units (Anderson, Hirst & Stoddart, 1966; Anderson & Stobbart, 1966; Lopez-Torrez et al., 2015).

A. *senegal* gum can be defined as a continuum of AGPs differing by their sugar, amino acid and mineral content and composition, sugar to amino acid ratio, polarity, number of charges,

molar mass, size and shape (Randall, Phillips & Williams, 1989; Islam, Phillips, Sljivo, Snowden & Williams, 1997; Renard, Lavenant-Gourgeon, Ralet & Sanchez, 2006; Mejia Tamayo, Nigen, Apolinar-Valiente, Doco, Williams, Renard & Sanchez, 2018). These AGPs can be separated according to their polarity using hydrophobic interaction chromatography (HIC) with the recovery of three fractions (Randall et al., 1989; Renard et al., 2006). These three fractions were historically named arabinogalactan (AG), arabinogalactan-protein (AGP) and glycoprotein (GP) according to their protein content and elution order. ~~However, all t~~The ability of these three fractions to bind the β-glucosyl Yariv's reagent suggests that they all belong to the AGP family ~~because of their reactivity to the Yariv's reactant~~ (Osman et al. 1993). Hence, to avoid any confusion, we named them HIC-F1 (arabinogalactan, AG), HIC-F2 (arabinogalactan-protein, AGP) and HIC-F3 (glycoprotein, GP) in their order of elution, reflecting also an increasing hydrophobic index. HIC-F1 is the most abundant fraction (85-92% of the whole gum) as compared to HIC-F2 (6-16% of the whole gum) and HIC-F3 (1-3% of the whole gum). The sugar composition was similar between the three fractions, with however a larger content of arabinose in HIC-F2 and HIC-F3 and a larger content of charged sugars in HIC-F1. HIC-F3 was the richest fraction in proteins with values around 25-40%, while the amount of proteins was around 8-10% and 0.5-1% for HIC-F2 and HIC-F1, respectively. These three HIC fractions differed also by their mean molar mass (M_w) and high M_w AGPs content (AGPs with M_w upper than 10^6 g.mol^{-1}). HIC-F1 was mainly composed of low M_w AGPs, while HIC-F2 and HIC-F3 were richest in high M_w AGPs.

In young red wines, it is advised to use Acacia *senegal* gum at a maximal concentration of 300 mg/L (Code International des Pratiques Œnologiques, Fiche Code OIV (12/72) – Edition 01/2015 II.3.3-7) even if no legal limit exists in the EC 606-2009. Before its addition in young red wines, the efficiency of A. *senegal* gum towards wine colloidal instability is evaluated according to an "efficacy test" of the International Oenological Codex (International

Oenological Codex: COEI-1-GOMARA, 2000). This "efficacy test" consists in determining the quantity of A. *senegal* gum required to prevent the flocculation of a colloidal iron hexacyanoferrate solution in hydro-alcoholic medium by calcium salt. Hence, the A. *senegal* gum efficiency towards wine colloidal instability is usually evaluated using a hydro-alcoholic – mineral solution which seems in appearance far enough from wine matrices on their biochemical and physicochemical properties. The colloidal stabilization of two so different matrices by A. *senegal* gum raises some questions on the colloidal stability mechanism and especially on the AGPs at the origin of this colloidal stabilization.

The aim of this study was to investigate the colloidal stabilizing properties of AGPs from A. *senegal* gum in three hydro-alcoholic solutions: a hydro-alcoholic – mineral solution, "wine-like" solution and young red wine. The AGPs responsible of the colloidal stability in the three hydro-alcoholic solutions were identified. Furthermore, the colloidal stabilization mechanism involving AGPs from A. *senegal* gum in hydro-alcoholic – mineral solution was characterized.

2. Materials and Methods

2.1. Materials

Instant spray dried Acacia *senegal* gum was provided by ALLAND & ROBERT Company - Natural and organic gums (Port Mort, France). A. *senegal* gum was fractionated by hydrophobic interaction chromatography (HIC) according to Renard et al. (Renard et al., 2006). Three HIC fractions were isolated ~~that were~~and named HIC-F1, HIC-F2 and HIC-F3 according to their elution order, and then their hydrophobic behaviour. The biochemical composition and structural properties (mean molar mass) of A. *senegal* gum and HIC fractions were described by Mejia-Tamayo (Mejia-Tamayo et al., 2018) and presented in supplementary data (Table S1).

The pronase was from s*treptomyces griseus* (lot 10165921001, Roche). The grape marc powder rich in polyphenols (64%) was provided by Grap'Sud Company (Cruviers-Lascours, France). The unstable young red wine (Cabernet sauvignon/Merlot, 2015) was provided by BioLaffort Company (Bordeaux, France). All other reagents were of analytical grade from Sigma-Aldrich (USA).

2.2. Hydrolysis of Acacia senegal gum and HIC-F1 fraction by pronase

A. *senegal* gum and HIC-F1 fraction were dissolved at a concentration of 10 $mg.ml^{-1}$ in ultra pure deionised water (18.2 mΩ resistivity) containing 0.02% NaN_3 and stirred overnight at room temperature. The pH was adjusted at 6.5 using a small aliquot of NaOH solution before to add pronase at a final concentration of 0.14 $mg.ml^{-1}$. The enzymatic hydrolysis occurred during 48h at 35°C. The enzymatic reaction was stopped by removing the pronase from the samples by centrifugation at 3000 rpm using a centricon Vivaspin 20 (cut-off of 50 000 Da). The hydrolysis products were also removed by the centrifugation step. The samples were then washed four times with ultra pure deionised water (18.2 mΩ resistivity) by centrifugation at 3000 rpm using a centricon Vivaspin 20 (cut-off of 50 000 Da), before their freeze-drying.

2.3. Preparation of Acacia senegal gum and its HIC fractions

Stock solution of A. *senegal* gum and HIC fractions were dissolved in ~~ultra pure~~ultra-pure deionised water (18.2 mΩ resistivity) and stirred overnight at room temperature. The solutions were centrifuged at 12 500 rpm for 30 min at 20°C to remove insoluble materials and air bubbles.

2.4. Electrophoretic mobility measurements

The electrophoretic mobility of A. *senegal* gum prepared in hydro-alcoholic solutions (tartaric acid: 3 $g.L^{-1}$; potassium sulfate: 1 $g.L^{-1}$; ethanol: 12% v/v) at pH 3.1, 3.5 and 4 was determined using a Zetasizer 1000 (Malvern, United Kingdom). The measurements were performed at 25°C. The data are the average of three measurements.

2.5. Multi-detector high performance size exclusion chromatography

HPSEC experiments were performed using a Shimadzu HPLC system (Shimadzu, Kyoto, Japan) coupled to one Shodex OHpak SB-G pre-column followed by four Shodex OHpak SB columns in series (SB 806 HQ, SB 805 HQ, SB 804 HQ and SB 803 HQ). 50 µl of A. *senegal* gum and HIC fractions solutions (1 $mg.ml^{-1}$) were injected. The elution was performed with 0.1 $mol.L^{-1}$ $LiNO_3$ solution containing 0.02% NaN_3 at a flow rate of 1 $ml.min^{-1}$ and 30°C.

The HPSEC system was fitted in series to a Dawn Heleos II multi-angle laser light scattering (Wyatt Technology Corp., Santa Barbara, Ca, USA) and an Optilab T-rEX refractometer (Wyatt Technology Corp., Santa Barbara, Ca, USA). The molar mass distribution and the weight-average molar mass (M_w) were calculated using ASTRA software 6.1.1.17 (Wyatt Technologies, Santa Barbara, CA). The data were analyzed using the Zimm's model (1st order) and a refractive index increment (dn/dc) of 0.155, 0.162, 0.160 and 0.145 $ml{\cdot}g^{-1}$ for A. *senegal* gum, HIC-F1, HIC-F2 and HIC-F3, respectively, as determined experimentally.

2.6. Colloidal stability of hydro-alcoholic - mineral solution

The hydro-alcoholic – mineral solution was prepared with ~~ultra pure~~ultra-pure deionised water (18.2 mΩ resistivity) according to the ~~International~~ Oenological International Codex (O.I.V.). This solution ~~It~~ was composed of tartaric acid (3 $g.L^{-1}$), potassium sulfate (1 $g.L^{-1}$), ethanol (12% v/v), potassium ferrocyanide (60 $mg.L^{-1}$) and iron ~~solution~~ (5 $mg.L^{-1}$~~‰~~). ~~When~~The addition of iron (Fe^{3+}) ~~was added~~ to the hydro-alcoholic – mineral solution

~~containing potassium ferrocyanide ($K[Fe(CN)_6]^{4-}$),~~induced the formation of a soluble "Prussian blue" colloidal solution of $K[Fe^{III}Fe^{II}(CN)_6]$ ~~is obtained~~. The hydro-alcoholic – mineral solution was stirred during 2 h at room temperature before to adjust ~~the~~its pH at 3.1 using NaOH ~~solution~~ (1 $mol.L^{-1}$). The hydro-alcoholic – mineral solution was then filtered through a 0.45 µm regenerated cellulose membrane (GE Healthcare Life Sciences, Germany). For the studies according to pH, the hydro-alcoholic – mineral solution was prepared at pH 3.1, 3.5 and 4.0.

The hydro-alcoholic – mineral solution was destabilized by the addition of $CaCl_2$ (22 $g.L^{-1}$) prepared in ultra-pure deionised water (18.2 mΩ resistivity). The added Ca^{2+} bound to $K[Fe^{III}Fe^{II}(CN)_6]$ inducing the formation of "Prussian blue" precipitates ($Ca[Fe^{III}Fe^{II}(CN)_6]_2$). Most of experiments were performed at a final $CaCl_2$ concentration of 0.67 $g.L^{-1}$. Some experiments were performed at a final concentration of 0.33, 0.5, 1 and 1.33 $g.L^{-1}$ to investigate the influence of calcium. Each measurement was triplicated.

The efficiency of A. *senegal* gum and its HIC fraction to prevent the colloidal mineral destabilization was studied by varying their concentration in the hydro-alcoholic – mineral solution. The final concentration of A. *senegal* gum or its HIC fractions in the hydro-alcoholic – mineral solution ranged between 0 and 1 $g.L^{-1}$. A. *senegal* gum or HIC fraction solutions were added to the hydro-alcoholic – mineral solution before the addition of $CaCl_2$ solution. Each measurement was triplicated.

2.7. Colloidal stability of hydro-alcoholic – grape marc solution and young red wine

The hydro-alcoholic – grape marc solution (wine-like medium) was prepared with ultra-pure deionised water (18.2 mΩ resistivity). It contained tartaric acid (2.7 $g.L^{-1}$), potassium sulfate (0.9 $g.L^{-1}$), grape marc powder (3 $g.L^{-1}$) and ethanol (12% v/v). The solution was gently stirred during 2 h at room temperature before to adjust the pH at 3.5 using NaOH solution (1

mol.L^{-1}). The solution was then filtered through a 0.45 µm regenerated cellulose membrane (GE Healthcare Life Sciences, Germany).

The colloidal destabilization of the hydro-alcoholic – grape marc solution and the young red wine was induced by cooling the solutions to 10°C. The efficiency of A. *senegal* gum and its HIC fraction to prevent the destabilization of the hydro-alcoholic – grape marc solution and the young red wine was studied at 10°C by varying their concentration between 0 and 2 g.L^{-1}. Each measurement was triplicated.

2.8. Characterization of the colloidal stability of hydro-alcoholic model solutions and young red wine

The colloidal stability of the hydro-alcoholic – mineral and hydro-alcoholic – grape marc solutions, and the young red wine was investigated using a Turbiscan Tower equipped with a pulsed near infrared light source (λ = 880 nm) and two synchronous detectors, a transmission (T) and a backscattering (BS) detectors (Formulaction, France). The samples were loaded into cylindrical glass tubes and scanned throughout its entire height. The transmittance (T, in %) was measured every 1 min and 50 sec during 24 h at 25°C for the hydro-alcoholic – mineral solutions and during 48 h at 10°C for the hydro-alcoholic – grape marc solutions and young red wine.

The transmittance (T) profiles were analyzed using the TowerSoft software, version 1.1.0.36 (Formulaction, France). ΔT (%) corresponded to the difference in transmittance between the $scan_i$ and the first scan. The Turbiscan Stability Index (TSI) was also determined as the following:

$$TSI = \sum_i \frac{\sum h\left|scan_i(h) - scan_{i-1}(h)\right|}{H}$$

The TSI corresponded to the transmittance variation at all measured position (h) throughout the entire height (H) of the sample between the $scan_i$ and the $scan_{i-1}$. The plot of TSI according to time corresponds to the kinetic behavior of the samples that takes into account all the physical phenomena (especially destabilization mechanism) occurring during the measurement.

The TSI kinetics were used to plot the TSI values at 24h in hydro alcoholic – mineral solution and 48h in hydro alcoholic – grape marc solution and young red wine according to AGPs concentration. This representation assimilated to a "stability curve" was used to experimentally determine the AGPs concentration, named critical concentration, necessary to obtain the colloidal stability of the solutions.

3. Results

3.1. Colloidal stabilization mechanism of the hydro-alcoholic – mineral solution by A. senegal gum

The colloidal stability of the hydro-alcoholic – mineral solution (pH 3.1) containing A. *senegal* gum was followed by measuring at 25°C the transmittance (T) of the solutions during 24h using a light scattering equipment. The figure 1 showed the temporal change in transmittance (ΔT) of three hydro-alcoholic – mineral solutions without and with 0.09 and 0.14 $g.L^{-1}$ of A. *senegal* gum (Figure 1A, 1B and 1C). After 24h, the transmittance (T) of the hydro-alcoholic – mineral solutions without and with 0.09 $g.L^{-1}$ of A. *senegal* gum increased respectively by 60% and 35% in the middle of the sample (cell height: 2 – 36 mm) reflecting a clarification of the solution. This phenomenon was confirmed by the loss of the blue color of the solutions after 24h (Figure 1A and 1B). The clarification resulted from the formation of a salt precipitate ($Ca[Fe^{III}Fe^{II}(CN)_6]_2$) between $K[Fe^{III}Fe^{II}(CN)_6]$ and Ca^{2+} that pelleted, as evidenced by the decrease of T by 5% and 2% after 24h in the bottom of the cell (cell height:

1 – 1.5 mm) for the solutions without and with 0.09 $g.L^{-1}$ of A. *senegal* gum, respectively (Figure 1A and 1B). On the other hand, the transmittance of the hydro-alcoholic – mineral solution containing 0.14 $g.L^{-1}$ of A. *senegal* gum was constant during the 24h of measurement, reflecting the colloidal stability of the solution. The influence of A. *senegal* gum concentration (0 – 0.14 $g.L^{-1}$) on the colloidal stability kinetics of the hydro-alcoholic – mineral solution was analyzed by plotting the TSI (Turbiscan Stability Index) according to time (Figure 2A). The increase of A. *senegal* gum concentration reduced and delayed the instability mechanism occurring in the hydro-alcoholic – mineral solution. The colloidal instability was totally prevented for an A. *senegal* gum concentration above around 0.11 $g.L^{-1}$. The minimal A. *senegal* gum concentration ($[AG]_{critical}$) necessary to obtain the hydro-alcoholic – mineral colloidal stability was determined by plotting the TSI values after 24h according to A. *senegal* gum concentration (stability curve) (Figure 2B). Below an A. *senegal* gum concentration of 0.05 $g.L^{-1}$, the TSI values at 24h was constant and similar to the control sample without A. *senegal* gum. In these experimental conditions, the concentration of A. *senegal* gum was too low. Above 0.05 $g.L^{-1}$ of A. *senegal* gum, the TSI values decreased progressively before to reach a constant TSI value (≤ 2) similar to the control without Ca^{2+} for A. *senegal* gum concentration upper than 0.11 $g.L^{-1}$. Based on the stability curve, the $[AG]_{critical}$ was 0.114 ± 0.002 $g.L^{-1}$ (Figure 2B).

The colloidal stabilization mechanism was further investigated by modifying the physicochemical condition as the pH of the solutions and the amount of Ca^{2+} added to induce the colloidal instability mechanism. The stability curves of hydro-alcoholic – mineral solutions prepared at pH 3.1, 3.5 and 4.0 are shown in Figure 3A. As the pH increased from 3.1 to 4.0, the stability curves were shifted towards lower A. *senegal* gum concentrations necessary to prevent the colloidal instability. The $[AG]_{critical}$ were 0.114 ± 0.002, 0.094 ± 0.003 and 0.064 ± 0.002 $g.L^{-1}$ at pH 3.1, 3.5 and 4.0, respectively. Hence, the colloidal

stabilizing properties of A. *senegal* gum were greatly influenced by pH and enhanced with its increase in this pH range. AGPs from A. *senegal* gum are weakly charged glycoproteins characterized by a global negative charge in aqueous solution for pH ranging from 2.0 to 10.0 (Burgess & Carless, 1984). Moreover, the negative AGPs μ_E increased from pH 2.0 to ~ 5.0 in aqueous solutions reflecting the increase of the global negative charge (Burgess & Carless, 1984; Schmitt, Sanchez, Thomas & Hardy, 1999). Thus, the electrophoretic mobility (μ_E) of A. *senegal* gum in hydro-alcoholic solutions prepared at pH 3.1, 3.5 and 4.0 was measured and plotted according to $[AG]_{critical}$ (Figure 3B). A good correlation was evidenced between A. *senegal* gum μ_E and its concentration necessary to stabilize the hydro-alcoholic – mineral solutions. The more the negative A. *senegal* gum μ_E was, the less the A. *senegal* gum quantity was required to prevent the colloidal instability. Hence, negative charges carried by AGPs were certainly involved in this colloidal stabilization mechanism.

Since the colloidal instability of the hydro-alcoholic – mineral solution is induced by the addition of Ca^{2+}, it was hypothesized that electrostatic interactions between Ca^{2+} and negative charges of AGPs could play an important role in the stabilization mechanism. Therefore, we determined the $[AG]_{critical}$ in hydro-alcoholic – mineral solutions (pH 3.1) containing different final Ca^{2+} concentrations (0.33 to 1.33 $g.L^{-1}$). A close linear relationship between the $[AG]_{critical}$ and the amount of Ca^{2+} added in the hydro-alcoholic – mineral solutions was obtained (Figure 4). The increase of Ca^{2+} concentration induced also the increase of $[AG]_{critical}$. Based on its structural and physicochemical properties, hyperbranched and negatively charged, AGPs from A. *senegal* gum appear as a natural mineral carrier that contains ~~~ 2 ~~3.4 wt% of ash for this Acacia gum sample, and especially Ca^{2+} (Anderson, Douglas, Morrison & Weiping, 1990; Debon & Tester, 2001; Mhinzi, 2003). Lamport and Varnai evidenced that Ca^{2+} bound to AGPs with a fairly strong binding constant of 6.5×10^{-6} $mol.L^{-1}$ (Lamport & Varnai, 2013). They also showed that the Ca^{2+} binding sites of AGPs

were not naturally fully saturated by Ca^{2+}. Hence, as expected, we can easily suggest that AGPs stabilized the hydro-alcoholic – mineral solutions by its electrostatic binding with Ca^{2+}, the driver of the instability mechanism.

3.2. Identification AGPs from A. senegal gum involved in the colloidal stability mechanism of the hydro-alcoholic – mineral solution

As previously mentioned, A. *senegal* gum is a continuum of AGPs differing by their biochemical, structural and physicochemical properties (Randall et al., 1989; Renard et al., 2006). To better identify the macromolecules involved in this colloidal stabilization mechanism, A. *senegal* gum was fractionated using Hydrophobic Interaction Chromatography (HIC). The three fractions obtained were named HIC-F1, HIC-F2 and HIC-F3 according to their elution order and consequently to their increasing hydrophobic index. The biochemical composition and some structural properties of A. *senegal* gum and its HIC fractions were previously described (Mejia-Tamayo et al., 2018) and presented in supplementary data (table 1). The three HIC fractions are composed of the same sugars (D-galactose, L-arabinose, D-glucuronic acid and 4-O-methyl-D-glucuronic acid) with some differences in their proportions. The arabinose to galactose (Ara/Gal) molar ratio was 0.69, 1.03 and 1.29 for HIC-F1, HIC-F2 and HIC-F3, respectively. HIC-F1was also richer in uronic acid (glucuronic and 4-O-methyl-glucuronic acids) than HIC-F2 and HIC-F3 fractions (21.7 wt% vs. 16.2 wt% and 14.4 wt%, respectively). Hence, the carbohydrate blocks of HIC-F1 were supposed to carry more negative charges than HIC-F2 and HIC-F3 ones. Biochemically, the main difference between HIC fractions was the protein content and consequently the protein/sugar ratio. HIC-F3 showed a higher amount of proteins (13.8 wt%) and then protein/sugar ratio (0.169) as compared to HIC-F2 (6.3 wt% and 0.069) and HIC-F1 (0.5 wt% and 0.005). Structurally, the three HIC fractions differed mainly by their mean molar mass (M_w) and high

346 molar mass (HM_w) macromolecules content ($M_w > 10^6$ $g.mol^{-1}$). HIC-F2 and HIC-F3 were
347 richer in protein-rich high molar mass (HM_w) AGPs than HIC-F1 (73, 56 and 3%,
348 respectively) (supplementary table 1).

349 The stability curves of the hydro-alcoholic – mineral solution in the presence of the three HIC
350 fractions are shown in the Figure 5. They can be classified from the most effective to the least
351 in terms of stabilization as: HIC-F3 > HIC-F2 > HIC-F1. Thus, the critical concentrations of
352 HIC-F1, HIC-F2 and HIC-F3 fractions were 0.570, 0.090 and 0.012 $g.L^{-1}$, respectively.
353 Though HIC-F3 was the minor fraction in weight (around 1 wt% of whole A. *senegal* gum),
354 its efficiency for the colloidal stabilization of the hydro-alcoholic – mineral solution was 48,
355 10 and 7.5 times larger than those of HIC-F1, A. *senegal* gum and HIC-F2, respectively.
356 Hence, the colloidal stability properties of A. *senegal* gum towards the hydro-alcoholic –
357 mineral solution were mainly due to its two minor fractions in weight, HIC-F2 and HIC-F3
358 (around 11 wt% of whole A. *senegal* gum), that were especially richer in protein-rich HM_w
359 AGPs than HIC-F1 (Table 1).

360 HIC-F1 (89 wt% of whole A. *senegal* gum) that was characterized by poor colloidal
361 stabilizing property contained also a low amount (3%) of protein-rich HM_w AGPs. To precise
362 whether the macromolecular origin of the colloidal stabilizing properties is due to this
363 fraction, its HM_w AGPs were removed by an enzymatic hydrolysis treatment using the
364 pronase, a protease mixture. Several studies showed the specific hydrolysis activity of pronase
365 for protein-rich HM_w AGPs from A. *senegal* gum without degrading and affecting the
366 structural properties of low M_w (LM_w) AGPs (Connolly, Fenyo & Vandevelde, 1988; Randall
367 et al., 1989; Flindt, Al-Assaf, Phillips & Williams, 2005; Mahendran, Williams, Phillips, Al-
368 Assaf & Baldwin, 2008; Renard, Lavenant-Gourgeon, Lapp, Nigen & Sanchez, 2014). The
369 refractive index (RI) signal and the M_w distribution of HIC-F1 before and after the enzymatic
370 treatment are shown in Figure 6A. The pronase hydrolyzed the protein-rich AGPs decreasing

371 the HM_w AGPs content from 3 to 1.7%, without affecting the quantity and the structural
372 properties of LM_w AGPs (Figure 6A). The colloidal stabilizing properties of the hydrolyzed
373 HIC-F1 towards the hydro-alcoholic – mineral solution were characterized and compared to
374 HIC-F1 (Figure 6C). The hydro-alcoholic – mineral solutions was totally unstable until 1.2
375 $g.L^{-1}$ of hydrolyzed HIC-F1, a concentration twice more than the minimal HIC-F1
376 concentration necessary to totally prevent the colloidal instability ($[HIC\text{-}F1]_{critical}$ = 0.570 $g.L^{-1}$).
377 Hence, the removal of less than 1.5% of AGPs from HIC-F1, corresponding to HM_w
378 AGPs, induced the loss of its colloidal stabilizing properties. The main contribution of
379 protein-rich HM_w AGPs was also confirmed by studying the colloidal stabilizing properties of
380 hydrolyzed A. *senegal* gum by pronase. After the enzymatic treatment, the content of protein-
381 rich HM_w ($M_w > 10^6$ $g.mol^{-1}$) AGPs decreased from 14 to 6% (Figure 6B). As observed for
382 HIC-F1, A. *senegal* gum also lost its stabilizing properties after the pronase treatment: the
383 hydro-alcoholic – mineral solutions containing 0.12 $g.L^{-1}$ of hydrolyzed A. *senegal* gum was
384 totally unstable while $[AG]_{critical}$ was found to be 0.114 $g.L^{-1}$. These results highlighted the
385 major role of the protein-rich AGPs in the colloidal stabilizing mechanism of the hydro-
386 alcoholic – mineral solution. Hence, HIC-F2 and HIC-F3 fractions prevented the colloidal
387 instability of the hydro-alcoholic – mineral solution (i.e. formation of salt precipitates) by
388 their electrostatic binding with Ca^{2+}. The key role of the protein-rich AGPs on the functional
389 properties of A. *senegal* gum was also evidenced by studying its interfacial properties
390 (Elmaman, Al-Assaf, Phillips & Williams, 2008). In this study, the removal of the protein-
391 rich AGPs by a pronase treatment resulted in the loss of the interfacial properties of A.
392 *senegal* gum.
393
394 *3.3. Colloidal stabilization of a hydro-alcoholic – grape marc solution and an unstable young*
395 *red wine by AGPs from A. senegal gum*

In order to correlate the results obtained on the hydro-alcoholic – mineral solution to the wine matrix, the stabilizing properties of A. *senegal* gum and its HIC fractions were characterized on an unstable synthetic hydro-alcoholic – grape marc solution (wine-like medium) and an unstable young red wine.

The hydro-alcoholic – grape marc solution and the young red wine that were stable at 25°C (control sample) were destabilized upon cooling to 10°C that induced the precipitation of the unstable colloidal substances as the coloring matter (Ribereau-Gayon et al., 2006; Alcade-Eon et al., 2014). The colloidal stability kinetics of the hydro-alcoholic – grape marc solution and the young red wine supplemented with A. *senegal* gum and HIC fractions were followed by measuring the transmittance of the solution during 48 h at 10°C. The increase of A. *senegal* gum concentration from 0 to 0.5 $g.L^{-1}$ led to the colloidal stabilization of the hydro-alcoholic – grape marc solution (Figure 7A). The solution supplemented with 0.5 $g.L^{-1}$ of A. *senegal* gum presented a similar kinetic behavior as the control sample at 25°C suggesting that AGPs from A. *senegal* gum totally prevented the colloidal instability. This result was in agreement with the use of A. *senegal* gum, and more globally the AGPs, as protective colloids in wines and model beverages to prevent the aggregation and precipitation of polyphenols and proteins (Ribereau-Gayon et al., 2006; Waters et al., 1994; Riou et al., 2002; Mateus et al., 2004; Luck, Liao, Murray, Grimmer, Warminski, Williamson, Lilley & Haslam, 1994; Liang, Liu, Qi, Su, Yu, Wang & He, 2013; Soares et al., 2009; de Freitas et al., 2003), and the chemical modifications of anthocyanins (Chung et al., 2016). The efficiency of A. *senegal* gum and its HIC fractions towards the colloidal instability of this hydro-alcoholic – grape marc solution were characterized by plotting the stability curves after 48h of kinetics (Figure 7B). The critical concentrations of A. *senegal* gum, HIC-F1, HIC-F2 and HIC-F3 fractions were found to be 0.245 ± 0.010, 0.996 ± 0.090, 0.118 ± 0.014 and 0.027 ± 0.003 $g.L^{-1}$, respectively. The colloidal stabilizing properties of A. *senegal* gum, HIC-F2 and HIC-F3 fractions were also

confirmed on an unstable young red wine (Figure 7C). They totally prevented the young red wine colloidal instability at 10°C for concentrations of 0.086 ± 0.007, 0.045 ± 0.006 and 0.015 ± 0.002 $g.L^{-1}$, respectively. Unlike the other two HIC fractions, HIC-F1 was not efficient for the colloidal stabilization of the young red wine even at a concentration of 2 $g.L^{-1}$ (data not shown).

4. Discussion

The colloidal stabilizing properties of A. *senegal* gum and its HIC fractions isolated from Hydrophobic Interaction Chromatography were investigated on three colloidal hydro-alcoholic matrices: a hydro-alcoholic – mineral matrix, a hydro-alcoholic – grape marc solution ("wine-like" matrix) and an unstable young red wine. Whatever the hydro-alcoholic matrix tested, the HIC fractions can be classified in the same following order according to their colloidal stabilizing efficiency: HIC-F1 << HIC-F2 < HICF3. A. *senegal* gum that is a mixture of the HIC fractions presented some intermediate properties between those of HIC-F1 and HIC-F2. Before its addition in young red wines,~~Usually,~~ A. *senegal* gum ~~added in young red wines~~ is usually chosen based on its ability to stabilize a hydro-alcoholic – mineral matrix. When we plot the critical concentrations of A. *senegal* gum and its HIC fractions determined in hydro-alcoholic – mineral solution as a function of those determined in hydro-alcoholic – grape marc solution or young red wine (Figure 8), a good correlation between both systems is obtained. The more the AGPs from A. *senegal* gum are efficient to stabilize the hydro-alcoholic – mineral solution, the better they are to stabilize the polyphenols in young red wines. Hence, these results confirmed and strengthened the relevance and the use of the hydro-alcoholic – mineral test for the evaluation of A. *senegal* gum colloidal stabilizing properties before its addition in young red wine.

In the hydro-alcoholic – mineral solution, the colloidal stability was assessed by the electrostatic binding of Ca^{2+}, the "positively charged" driver of the colloidal instability, with the negatively charged AGPs. According to the monosaccharide and amino acid compositions of Acacia *senegal* gum (Mejia-Tamayo et al., 2018), the negative charges of AGPs are carried out both by the carbohydrate moiety through the carboxylic groups of glucuronic and 4-O-methyl glucuronic acid monosaccharides, and the polypeptidic backbone by the carboxylic groups of aspartic and glutamic acid amino acid side chains. The content and proportion of these negatively charged uronic acids and amino acids are fraction dependent with a large excess of uronic acids in the three fractions. HIC-F1 has a higher uronic acid content (20.9 wt% of whole fraction) as compared to HIC-F2 and HIC-F3 (14.9 wt% and 11.7 wt%, respectively) (supplementary table 1). Recently, Grein-Iankovski et al. (2018) characterized an acid dissociation constant (pK_a) between 3 and 4 for the AGPs from A. *senegal* gum that was attributed to the carboxylic group of glucuronic acids. This chemical property suggests a partial ionization of the carboxylic groups in the range of the pH studied in the hydro-alcoholic solutions, and moreover the increase of the negative charge of AGPs with the increase of pH from 3.1 to 4.0. This result is in well accordance with the decrease of the critical concentration of A. *senegal* gum when the pH is increased from 3.1 to 4.0. ~~Recently,~~ ~~t~~The binding of Ca^{2+} with the carboxyl group of two uronic acids of a conserved O-Hyp-linked arabinogalactan polysaccharide was demonstrated using molecular dynamic simulations (Lamport & Varnai, 2013). Hence, based on the excess of uronic acid in the three HIC fractions and the molecular dynamic simulations it could be expected as a first approximation that the mineral colloidal stability occurred mainly by the binding of Ca^{2+} to the uronic acids of carbohydrate blocks. However, our results showed that HIC-F1, the richest fraction in uronic acids, had the weakest colloidal stabilizing properties, while HIC-F3, the one with the least uronic acids content, was the most effective fraction for the colloidal

stabilization of the hydro-alcoholic – mineral solution (Figure 5). Hence, the stabilizing properties of AGPs could not be only explained by their uronic acids content. We also showed a significant decrease of the stabilizing properties of HIC-F1 and A. *senegal* gum after the hydrolysis of their protein-rich AGPs by a pronase treatment. The pronase is a cocktail of proteases hydrolyzing the accessible polypeptidic backbone of protein-rich AGPs without degrading the low molar mass (LM_w) AGPs poor in proteins (Renard et al. 2014). This enzymatic treatment gave rise to macromolecules presenting similar molar masses (M_w from 1.8 to $6.0x10^5$ $g.mol^{-1}$) and conformational properties as low molar mass (LM_w) AGPs naturally found in A. *senegal* gum (Connolly et al., 1988, Randall et al., 1989, Aoki, Al-Assaf, Katayama & Phillips, 2007, Renard et al., 2014). Since the conformational properties, and probably the sugar organization, of the released carbohydrate blocks of AGPs was seemingly not disturbed by the pronase treatment, this suggested that the uronic acids of the carbohydrate blocks were certainly not directly involved in the electrostatic Ca^{2+} binding in this colloidal stability test. Similar results were obtained on AGPs purified from a red wine by Waters et al. These authors showed that the greatest protein haze protective activity in Chardonnay wine was reached with AGPs presenting the highest protein content. Moreover, this protective activity was not affected by the sugar hydrolysis of AGPs using α-arabinofuranosidase and endo-(1→6)-β-D-galactanase, while it was totally lost when the protein moiety was altered with the loss of 75% of initial protein after smith degradation treatment (Waters et al., 1994). These results revealed the key role of the accessible polypeptidic backbone of AGPs in their colloidal stabilizing properties. In the hydro-alcoholic – mineral solution, it could be hypothesized that the electrostatic binding of Ca^{2+} occurred with only the negatively charged amino acids (aspartic and glutamic acids) or with the involvement of both negatively charged amino acids and uronic acid monosaccharides localized close to the protein backbone.

As observed in the hydro-alcoholic – mineral solution, the protein-rich AGPs from A. *senegal* gum, HIC-F2 and HIC-F3 fractions, were also found to be the most effective for the colloidal stabilization of the hydro-alcoholic – grape marc solution and the unstable young red wine. The surface and colloidal stabilizing properties of the protein-rich AGPs were previously demonstrated in other type of matrices. After A. *senegal* gum fractionation by size exclusion chromatography (SEC) and hydrophobic interaction chromatography (HIC), Ray et al. showed that the protein-rich AGPs made the best emulsions in model beverage (Ray, Bird, Iacobucci & Clark, 1995). Protein-rich AGPs were also found to be the most effective in decreasing the interfacial tension of n-hexadecane-water interface (Castellani, Al-Assaf, Axelos, Phillips & Anton, 2010), to preferentially adsorb at the interface of latex dispersions (Snowden, Phillips & Williams, 1987) and oil droplets (Randall, Phillips & Williams, 1988), and to stabilize carbon nanotube dispersions (Li, Zhang, Jin & Cai, 2018).

The stabilizing properties of the protein-rich AGPs towards such a chemical diversity of molecules (minerals, polyphenols, proteins, oils, latex, etc…) could be relied to their intrinsic properties. Structurally, the three HIC fractions seems not so different. AGPs from these fractions are hyperbranched glycoproteins adopting more or less extended ellipsoidal conformations (Sanchez, Schmitt, Kolodziejczyk, Lapp, Gaillard & Renard, 2008; Renard, Garnier, Lapp, Schmitt & Sanchez, 2012; Renard, Garnier, Lapp, Schmitt & Sanchez, 2013; Renard et al., 2014; Lopez-Torrez et al., 2015). AGPs from HIC-F2 and HIC-F3 fractions also appeared as more “flexible” than those of HIC-F1 (Mejia-Tamayo et al., 2018). Biochemically, HIC fractions presented some more marked differences, especially in their protein content and consequently in their protein to sugar ratio (supplementary table 1) that influenced their hydrophobic and hydration properties (Mejia-Tamayo et al., 2018). HIC-F1, HIC-F2 and HIC-F3 were eluted in that order according to their protein content and increasing hydrophobic behavior. From our results, the higher the HIC fraction is rich in

protein, the more effective it is for the colloidal stabilization of the three hydro-alcoholic solutions. In the hydro-alcoholic – grape marc solution and young red wine, these results were in accordance with the putative stabilization of polyphenols by their binding with AGPs via the establishment of hydrophobic interactions and hydrogen bonding (de Freitas et al., 2003; Mateus et al., 2004; Soares et al., 2009; Soares et al., 2012; Chung et al., 2016). Hence, the protein content and certainly the amino acids composition and distribution in the protein backbone of AGPs from A. *senegal* gum appeared as the main factor for the expression of their colloidal stabilizing properties in hydro-alcoholic matrices. This behavior agrees with the work performed by Dickinson et al. dealing with the surface properties of Acacia gums. Based on the surface activity of various Acacia gums with different protein content, these authors previously evidenced a good correlation between the Acacia gum protein content and its interfacial properties (Dickinson, Murray, Stainsby & Anderson, 1988; Dickinson, 2003). The protein content appeared also as essential for the colloidal stabilizing properties of mannoproteins, other glycoproteins considered as protective colloids in wine. The addition of mannoproteins containing a high proportion of proteins (10 to 30%) to red wine prevented the coloring matter precipitation and protein haze in white wine (Waters et al., 1994a; Escot et al., 2001; Charpentier, Escot, Gonzalez, Dulau & Feuillat, 2004; Poncet et al., 2007), while the mannoproteins with a low protein content were devoid of protective activity (Charpentier et al., 2004; Guadalupe, Palacios & Ayestaran, 2007; Poncet et al., 2007; Guadalupe & Ayestaran, 2008).

It is useful to remember that AGPs are constituted by a protein backbone covalently linked to hyperbranched carbohydrate blocks that partially hindered it from its environment. Therefore, if we consider the protein as the major component for the colloidal stabilizing properties of AGPs, it would seem appropriate to consider not only the protein content but also its accessibility to its environment that is closely link to the rate of glycosylation. HIC-F1,

presenting the weakest colloidal stabilizing properties, is highly glycosylated as compared to HIC-F2 and HIC-F3: their protein to sugar ratios (w/w) were 0.005, 0.069 and 0.169, respectively. The high glycosylation rate of HIC-F1 cause the protein less accessible to its environment as demonstrated by its resistance to the protein hydrolysis assay (Flindt et al., 2005; Renard et al., 2014). Moreover, the rate of glycosylation also influenced the structural and physicochemical properties of HIC fractions. The more the AGPs were glycosylated, then hydrated, the less their flexibility and hydrophobic behavior were marked (Mejia Tamayo et al., 2018). Therefore, we can advance that the surface properties of AGPs are mainly due to the physicochemical properties of their protein backbone which are subtly modulated and controlled by their rate of glycosylation.

5. Conclusion

In this research, the colloidal stabilizing properties of arabinogalactan-proteins from A. *senegal* gum in hydro-alcoholic – mineral and hydro-alcoholic – polyphenols solutions were investigated. The AGPs prevented the colloidal instability of both calcium iron hexacyanoferrate salts in “model” hydro-alcoholic solution and polyphenols in young red wine. A good relationship was evidenced between the stabilizing properties of AGPs determined in these two hydro-alcoholic solutions. The protein moiety of the AGPs appeared to be essential for these functional properties whatever the hydro-alcoholic solutions. The more the AGPs were rich in proteins, the more their colloidal stabilizing efficiency were. In the hydro-alcoholic – mineral solution, the AGPs avoided the precipitation of potassium ferrocyanide salts by their electrostatic binding with Ca^{2+}, the driver of the instability.

Acknowledgements

The authors would like to thank BioLaffort Company (Bordeaux, France) for the financial support and Alland&Robert Company (Port-Mort, France) for the gift of Acacia *senegal* gum sample.

References

Akiyama, Y., Eda, S., & Kato K. (1984). Gum Arabic is a kind of arabinogalactan protein. *Agricultural and Biological Chemistry*, *48*, 235-237.

Alcade-Eon, C., Garcia-Estévez, I., Puente, V., Rivas-Gonzalo, J.C., & Escribano-Bailon, M.T. (2014). Color stabilization of red wines. A chemical and colloidal approach. *Journal of Agricultural and Food Chemistry, 62*, 6984-6994.

Anderson, D.M.W., Hirst, E., & Stoddart, J.F. (1966). Studies on uronic acid materials Part XVII some structural features of Acacia *senegal* gum (gum Arabic). *Journal of the Chemical Society C: Organic*, 1959-1966.

Anderson, D.M.W., & Stoddart, J.F. (1966). Studies on uronic acid materials Part XV. The use of molecular-sieve chromatography in studies on Acacia senegal gum (Gum Arabic). *Carbohydrate Research, 2*, 104-114.

Anderson, D.M.W., Douglas, D.M.B., Morrison, N.A., & Weiping, W. (1990). Specifications for gum Arabic (Acacia *senegal*); analytical data for samples collected between 1904 and 1989. *Food Additives and Contaminants, 7*, 303-321.

Aoki, H., Al-Assaf, S., Katayama, T., & Phillips, G.O. (2007). Characterization and properties of Acacia senegal (L.) Willd. Var. senegal with enhanced properties (Acacia (sen) SUPER GUM (TM): Part 2- Mechanism of the maturation process. *Food Hydrocolloids, 21*, 329-337.

Burgess, D.J., & Carless, J.E. (1984). Microelectrophoretic studies of gelatin and Acacia for the prediction of complex coacervation. *Journal of Colloid and Interface Science, 98*, 1-8.

593 Castellani, O., Al-Assaf, S., Axelos, M., Phillips, G.O., & Anton, M. (2010). Hydrocolloids
594 with emulsifying capacity. Part-2 Adsorption properties at the n-hexadecane-water interface.
595 *Food Hydrocolloids, 24*, 121-130.
596 Charpentier, C., Escot, S., Gonzalez, E., Dulau, L., & Feuillat, M. (2004). Influence of yeast
597 glycosylated proteins on tannins aggregation in model solution. *Journal International des*
598 *Sciences de la Vigne et du Vin, 38*, 209-218.
599 Chung, C., Rojanasasithara, T., Mutilangi, W., & McClements, D.J. (2016). Enhancement of
600 colour stability of anthocyanins in model beverages by gum Arabic addition. *Food Chemistry,*
601 *201*, 14-22.
602 Connolly, S., Fenyo, J.C., & Vandevelde, M.C. (1988). Effect of a proteinase on the
603 macromolecular distribution of Acacia *senegal* gum. *Carbohydrate Polymers, 8*, 23-32.
604 Debon, S.J.J., & Tester, R.F. (2001). In vitro binding of calcium, iron and zinc by non-starch
605 polysaccharides. *Food Chemistry, 73*, 401-410.
606 Dickinson, E., Murray, B.S., Stainsby, G., & Anderson, D.M.W. (1988). Surface activity and
607 emulsifying behavior of some Acacia gums. *Food Hydrocolloids, 2*, 477-490.
608 Dickinson, E. (2003). Hydrocolloids at interfaces and the influence on the properties of
609 dispersed systems. *Food Hydrocolloids, 17*, 25-39.
610 de Freitas, V., Carvalho, E., & Mateus, N. (2003). Study of carbohydrate influence on protein-
611 tannin aggregation by nephelometry. *Food Chemistry, 81*, 503-509.
612 Dupin, I.V.S., Stockdale, V.J., Williams, P.J., Jones, G.P., Markides, A.J., & Waters, E.J.
613 (2000). *Saccharomyces cerevisiae* mannoproteins that protect wine from protein haze:
614 evaluation of extraction methods and immunolocalization. *Journal of Agricultural and Food*
615 *Chemistry, 48*, 1086-1095.

Elmaman, M., Al-Assaf, S., Phillips, G.O., & Williams, P.A. (2008). Studies on Acacia exudate gums: Part VI. Interfacial rheology of *Acacia senegal* and *Acacia seyal*. *Food Hydrocolloids, 22*, 682-689.

Escot, S., Feuillat, M., Dulau, L., & Charpentier, C. (2001). Release of polysaccharides by yeasts and the influence of released polysaccharides on colour stability and wine astringency. *Australian Journal of Grape and Wine research, 7*, 153-159.

Flindt, C., Al-Assaf, S., Phillips, G.O., & Williams, P.A. (2005). Studies on Acacia exudate gums: Part V. Structural features of Acacia *seyal*. *Food Hydrocolloids, 19*, 687-701.

Gerbaud, V., Gabas, N., Blouin, J., & Crachereau, J.C. (2010). Stuy of wine acid salt stabilization by addition of carboxymethylcellulose (CMC) : comparison with the « protective colloids » effect. *Journal International des Sciences de la Vigne et du Vin, 44*, 231-242.

Gordillo, B., Cejudo-Bastante, M.J., Rodríguez-Pulido, F.J., Jara-Palacios, M.J., Ramírez-Pérez, P., González-Miret, M.L., & Heredia, F.J. (2014) Impact of adding white pomace to red grapes on the phenolic composition and color stability of syrah wines from a warm climate. *Journal of Agricultural and Food Chemistry, 62*, 2663-2671.

Grein-Iankovski, A., Ferreira, J.G.L., Orth, E.S., Sierakowski, M.R., Cardoso, M.B., Simas, F.F., & Riegel-Vidotti, I.C. (2018). A comprehensive study of the relation between structural and physical chemical properties of acacia gums. *Food Hydrocolloids, 85*, 167-175.

Guadalupe, Z., Palacios, A., & Ayestaran, B. (2007). Maceration enzymes and mannoproteins: A possible strategy to increase colloidal stability and color extraction in red wines. *The Journal of Agricultural and Food Chemistry, 55*, 4854-4862.

Guadalupe, Z., & Ayestaran, B. (2008). Effect of commercial mannoprotein addition on polysaccharide, polyphenolic, and color composition in red wines. *The Journal of Agricultural and Food Chemistry, 56*, 9022-9029.

Idris, O.H.M., Williams, P.A., & Phillips, G.O. (1998). Characterization of gum from Acacia senegal trees of different age and location using multidetection gel permeation chromatography. *Food Hydrocolloids, 12*, 379-388.

International Oenological Codex: COEI-1-GOMARA, 2000.

Islam, A., Phillips, G., Sljivo, A., Snowden, M., & Williams, P. (1997). A review of recent developments on the regulatory, structural and functional aspects of gum Arabic. *Food Hydrocolloids, 11*, 493-505.

Lamport, D.T.A., & Varnai, P. (2013). Periplasmic arabinogalactan glycoproteins act as a calcium capacitor that regulates plant growth and development. *New Phytologist, 197*, 58-64.

Li, X., Zhang, H., Jin, Q., & Cai, Z. (2018). Contribution of arabinogalactan protein to the stabilization of single-walled carbon nanotubes in aqueous solution of gum Arabic. *Food Hydrocolloids, 78*, 55-61.

Liang, M., Liu, R., Qi, W., Su, R., Yu, Y., Wang, L., & He, Z. (2013). Interaction between lysozyme and procyanidin: Multilevel structural nature and effect of carbohydrates. *Food Chemistry, 138*, 1596-1603.

Lopez-Torrez, L., Nigen, M., Williams, P., Doco, T., & Sanchez, C. (2015). Acacia *senegal* vs. Acacia *seyal* gums – Part 1: Composition and structure of hyperbranched plant exudates. *Food Hydrocolloids, 51*, 41-53.

Luck, G., Liao, H., Murray, N.J., Grimmer, H.R., Warminski, E.E., Williamson, M.P., Lilley, T.H., & Haslam, E. (1994). Polyphenols, astringency and proline-rich proteins. *Phytochemistry, 37*, 357-371.

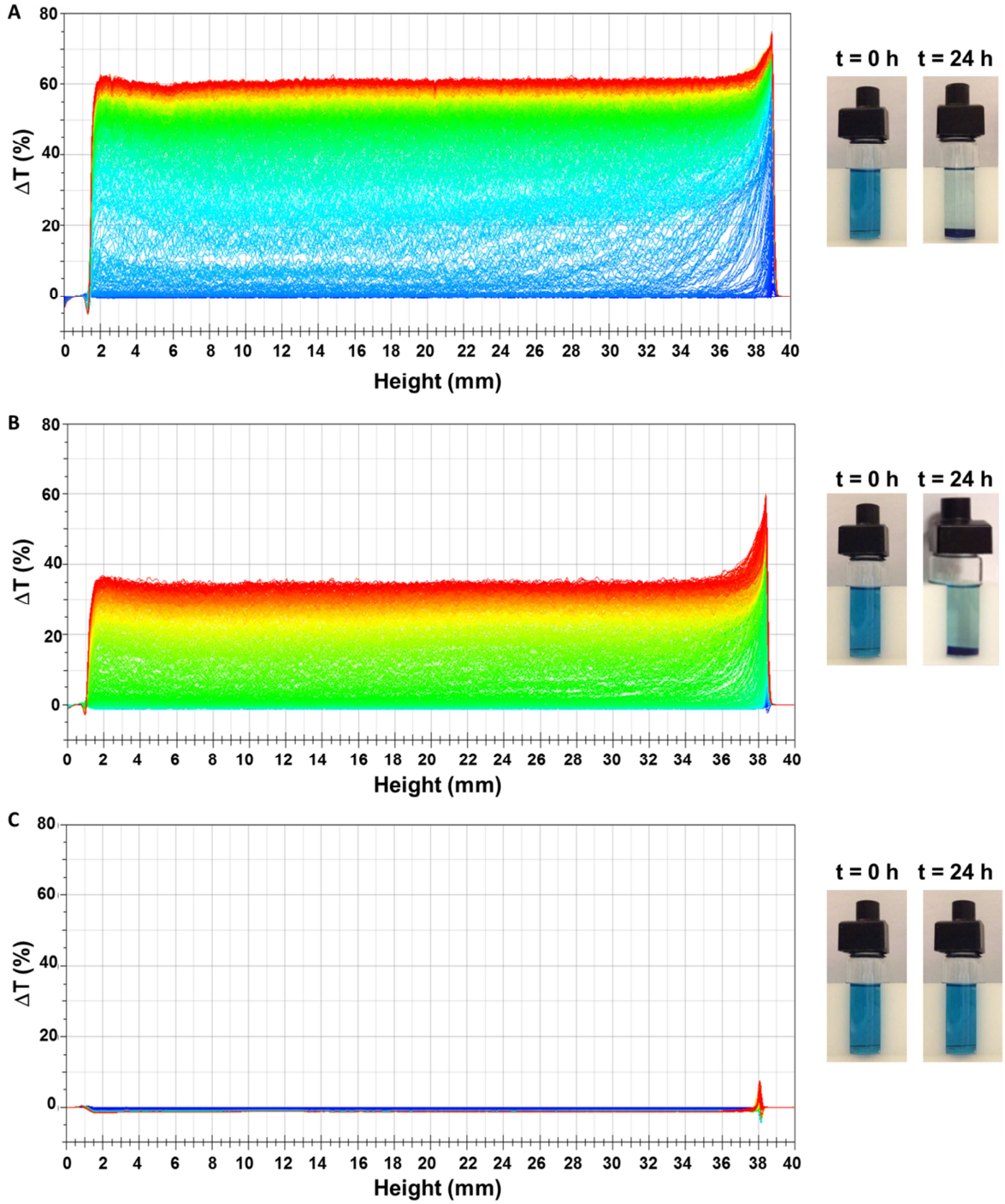
Mahendran, T., Williams, P.A., Phillips, G.O., Al-Assaf, S., & Baldwin, T.C. (2008). New insights into the structural characteristics of the arabinogalactan-protein (AGP) fraction of gum Arabic. *Journal of Agricultural and Food Chemistry, 56*, 9269-9276.

664 Mateus, N., Carvalho, E., Luis, C., & de Freitas, V. (2004). Influence of the tannin structure
665 on the disruption effect of carbohydrates on protein-tannin aggregates. *Analytica Chimica*
666 *Acta, 513,* 135-140.
667 Mejia-Tamayo, V., Nigen, M., Apolinar-Valiente, R., Doco, T., Williams, P., Renard, D., &
668 Sanchez, C. (2018). Flexibility and hydration of amphiphilic hyperbranched arabinogalactan-
669 protein from plant exudate: a volumetric perspective. *Colloids and Interface, 2*, 1-24.
670 Mhinzi, G.S. (2003). Intra-species variation of the properties of gum exudates from Acacia
671 *senegal var. senegal* and Acacia *seyal var. fistula* from Tanzania. *Bulletin of the Chemical*
672 *Society of Ethiopia*, 17, 67-74.
673 Osman, M.E., Menzies, A.R., Williams, P.A., Phillips, G.O., & Baldwin, T.C. (1993). The
674 molecular characterization of the polysaccharide gum from *Acacia senegal*. *Carbohydrate*
675 *Research, 246*, 303-318.
676 Pérez□Lamela, C., García□Falcón, M.S., Simal□Gándara, J., & Orriols□Fernández,
677 I. (2007). Influence of grape variety, wine system and enological treatments on the colour
678 stability of young red wines. *Food Chemistry, 101*, 601-606.
679 Poncet-Legrand, C., Doco, T., Williams, P., & Vernhet, A. (2007). Inhibition of grape seed
680 tannin aggregation by wine mannoproteins: effect of polysaccharide molecular weight.
681 *American Journal of Enology and Viticulture, 58*, 87-91.
682 Randall, R.C., Phillips, G.O., & Williams, P.A. (1988). The role of the proteinaceous
683 component on the emulsifying properties of gum arabic. *Food Hydrocolloids, 2*, 131-140.
684 Randall, R.C., Phillips, G.O., & Williams, P.A. (1989). Fractionation and characterization of
685 gum from Acacia *senegal*. *Food Hydrocolloids, 3*, 65-75.
686 Ray, A.K., Bird, P.B., Iacobucci, A.I., & Clark, B.C. (1995). Functionality of gum Arabic.
687 Fractionation, characterization and evaluation of gum fractions in citrus oil emulsions and
688 model beverages. *Food Hydrocolloids, 9*, 123-131.

689 Renard, D., Lavenant-Gourgeon, L., Ralet, M.C., & Sanchez C. (2006). Acacia *senegal* gum:
690 continuum of molecular species differing by their protein to sugar ratio, molecular weight,
691 and charges. *Biomacromolecules, 7*, 2637-2649.
692 Renard, D., Garnier, C., Lapp, A., Schmitt, C., & Sanchez, C. (2012). Structure of
693 arabinogalactan-protein from Acacia gum: From porous ellipsoids to supramolecular
694 architectures. *Carbohydrate Polymers, 90*, 322-332.
695 Renard, D., Garnier, C., Lapp, A., Schmitt, C., & Sanchez C. (2013). Corrigendum to
696 "Structure of arabinogalactan-protein from Acacia gum: From porous ellipsoids to
697 supramolecular architectures" [*Carbohydrate Polymers* 90 (2012) 322-332]. *Carbohydrate*
698 *Polymers, 97*, 864-867.
699 Renard, D., Lavenant-Gourgeon, L., Lapp, A., Nigen, M., & Sanchez, C. (2014). Enzymatic
700 hydrolysis studies of arabinogalactan-protein structure from Acacia gum: The self-similarity
701 hypothesis of assembly from a common building block. *Carbohydrate Polymers, 112*, 648-
702 661.
703 Ribéreau-Gayon, P., Glories, Y., Maujean, A., & Dubourbieu, D. (2006). *Handbook of*
704 *Enology. Vol. 2. The Chemistry of Wine Stabilization and Treatments*, 2nd ed.; Wiley:
705 Chichester, UK.
706 Riou, V., Vernhet, A., Doco, T., & Moutounet, M. (2002). Aggregation of grape seed tannins
707 in model wine – effect of wine polysaccharides. *Food Hydrocolloids, 16*, 17-23.
708 Sanchez, C., Schmitt, C., Kolodziejczyk, E., Lapp, A., Gaillard, C., & Renard, D. (2008). The
709 Acacia gum arabinogalactan fraction is a thin oblate ellipsoid: A new model based on small-
710 angle neuron scattering and ab initio calculation. *Biophysical Journal, 94*, 629-639.
711 Schmitt, C., Sanchez, C., Thomas, F., & Hardy, J. (1999). Complex coacervation between β-
712 lactoglobulin and acacia gum in aqueous medium. *Food Hydrocolloids, 13*, 483-496.

713 Snowden, M.L., Phillips, G.O., & Williams, P.A. (1987). Functional characteristics of gum
714 arabic. *Food Hydrocolloids, 1*, 291-300.
715 Soares, S.I., Gonçalves, R.M., Fernandes, I., Mateus, N., & de Freitas, V. (2009). Mechanistic
716 approach by which polysaccharides inhibit α-amylase/procyanidin aggregation. *Journal of*
717 *Agricultural and Food Chemistry, 57*, 4352-4358.
718 Soares, S., Mateus, N., & de Freitas, V. (2012). Carbohydrates inhibit salivary proteins
719 precipitation by condensed tannins. *Journal of Agricultural and Food Chemistry, 60*, 3966-
720 3972.
721 Teissedre, P.L. (2012). Arabic Gum in Oenology. In: Kennedy J.F, Phillips G.O., Williams
722 P.A. (eds) Arabic gum. RSC Publishing, Cambridge.
723 Waters, E.J., Pellerin, P., & Brillouet, J-M. (1994). A wine arabinogalactan-protein that
724 reduces heat-induced wine protein haze. *Bioscience Biotechnology and Biochemistry, 58*, 43-
725 48.
726 Waters, E.J., Pellerin, P., & Brillouet, J-M. (1994a). A Saccharomyces mannoprotein that
727 protects wine from protein haze. *Carbohydrate polymers, 23*, 185-191.
728 Williams, P.A., & Phillips, G.O. (2000). Gum Arabic. In G.O. Phillips, & P.A. Williams
729 (Eds.), Handbook of hydrocolloids, Boca Raton: CRC Press.
730

731 Figure 1. Transmittance changes of hydro-alcoholic – mineral solutions without (A) and with
732 0.09 (B) and 0.14 g.L^{-1} (C) of A. *senegal* gum. The transmittance was registered at 25°C
733 during 24h. Pictures of the solutions before and after 24h of kinetic are presented on the right.

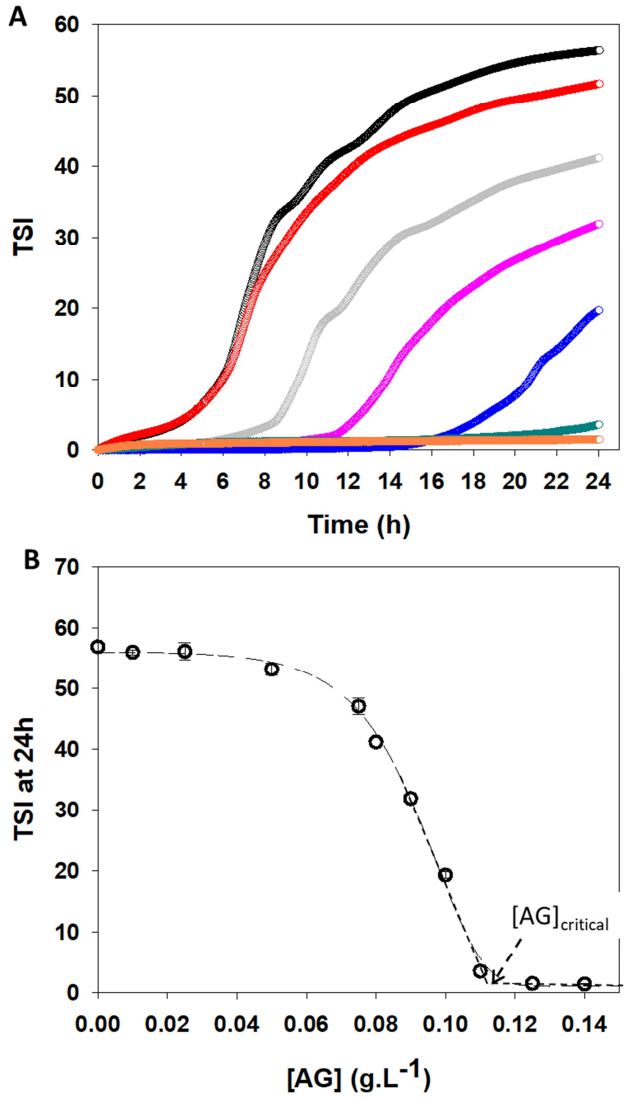


734

735

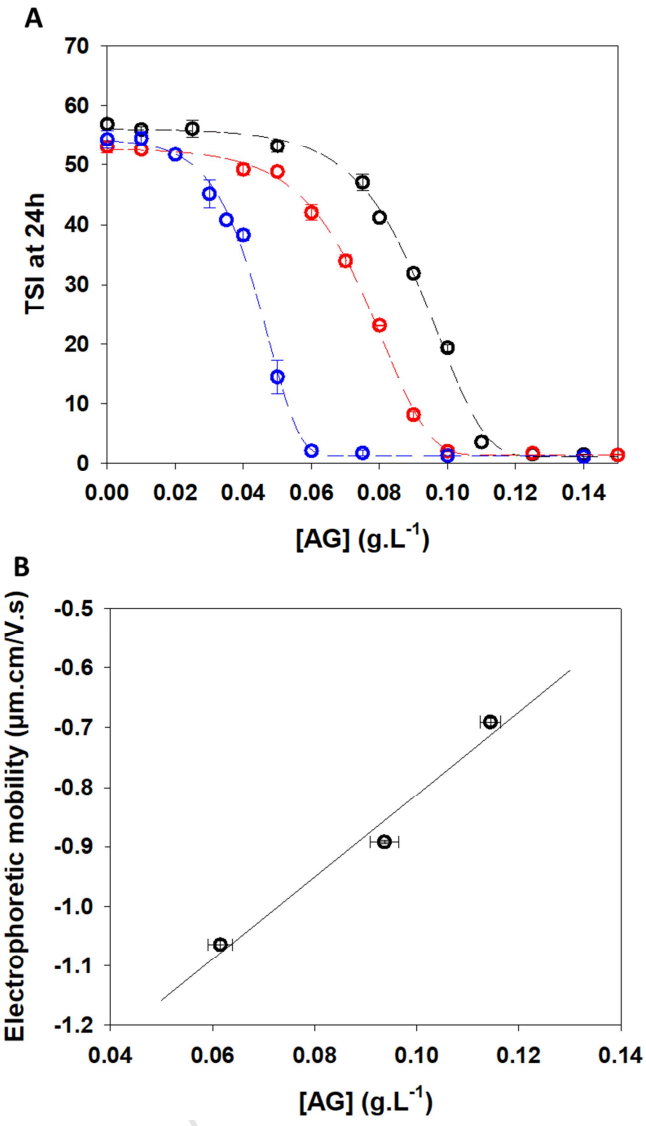
736

737 Figure 2. (A) Colloid stability kinetics of hydro-alcoholic – mineral solutions containing
738 various A. *senegal* gum concentrations: 0 (●), 0.05 (●), 0.08 (●), 0.09 (●), 0.10 (●), 0.11 (●)
739 and 0.14 (●) $g.L^{-1}$. (B) Colloidal stability curve of hydro-alcoholic – mineral solution in
740 presence of A. *senegal* gum after 24h of kinetic. The experiments were performed at 25°C.
741 The line (figure 2B) is shown to guide the eyes. The experiments were triplicated.
742



743
744
745
746

747 Figure 3. (A) Colloidal stability curves of hydro-alcoholic – mineral solutions in presence of
748 A. *senegal* gum (AG) at pH 3.1 (○), 3.5 (○) and 4.0 (○) after 24h of kinetic. (B) Relationship
749 between the electrophoretic mobility of A. *senegal* gum (AG) and its critical concentration in
750 hydro-alcoholic – mineral solutions. The lines (figure 3A) are shown to guide the eyes. The
751 experiments were triplicated.



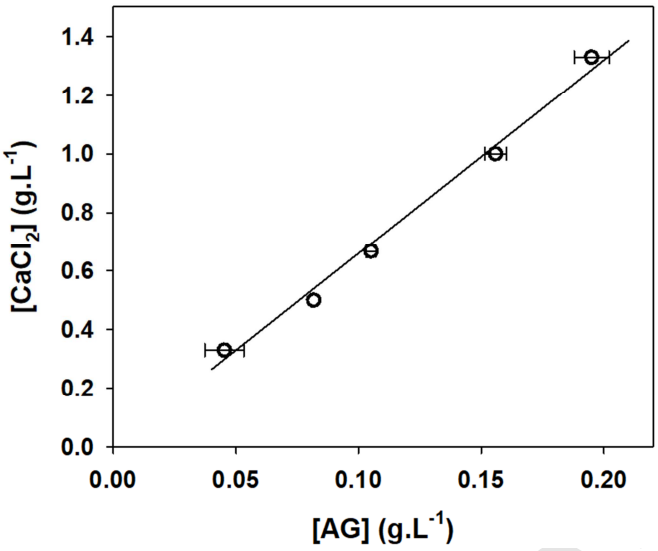
752

753

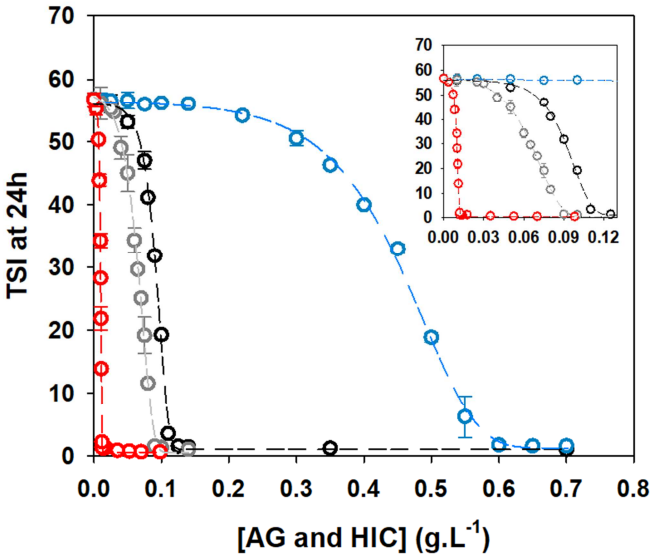
754

755

Figure 4. Relationship between the concentration of Ca^{2+} in the hydro-alcoholic – mineral solution and the critical stabilizing concentration in A. *senegal* gum ($[AG]_{crit}$). The experiments were triplicated.



774 Figure 5. Colloidal stability curves of hydro-alcoholic – mineral solution in presence of A.
775 *senegal* gum (○), HIC-F1 (○), HIC-F2 (○) and HIC-F3 (○) fractions after 24h of kinetic. The
776 experiments were performed at 25°C. The lines are shown to guide the eyes. The inset figure
777 is a zoom of the left part. The experiments were triplicated.
778



779
780
781

Figure 6. Molar mass distribution (thick line) and normalized refractive index signal (thin line) of HIC-F1 (A) and A. *senegal* gum (B) before (black) and after (red) pronase treatment. Colloidal stability curves of hydro-alcoholic – mineral solution in presence of HIC-F1 (C) and A. *senegal* gum (D) before (○) and after (●) pronase treatment after 24h of kinetic. The lines (figures 6C and 6D) are shown to guide the eyes. The colloidal stability experiments were triplicated.

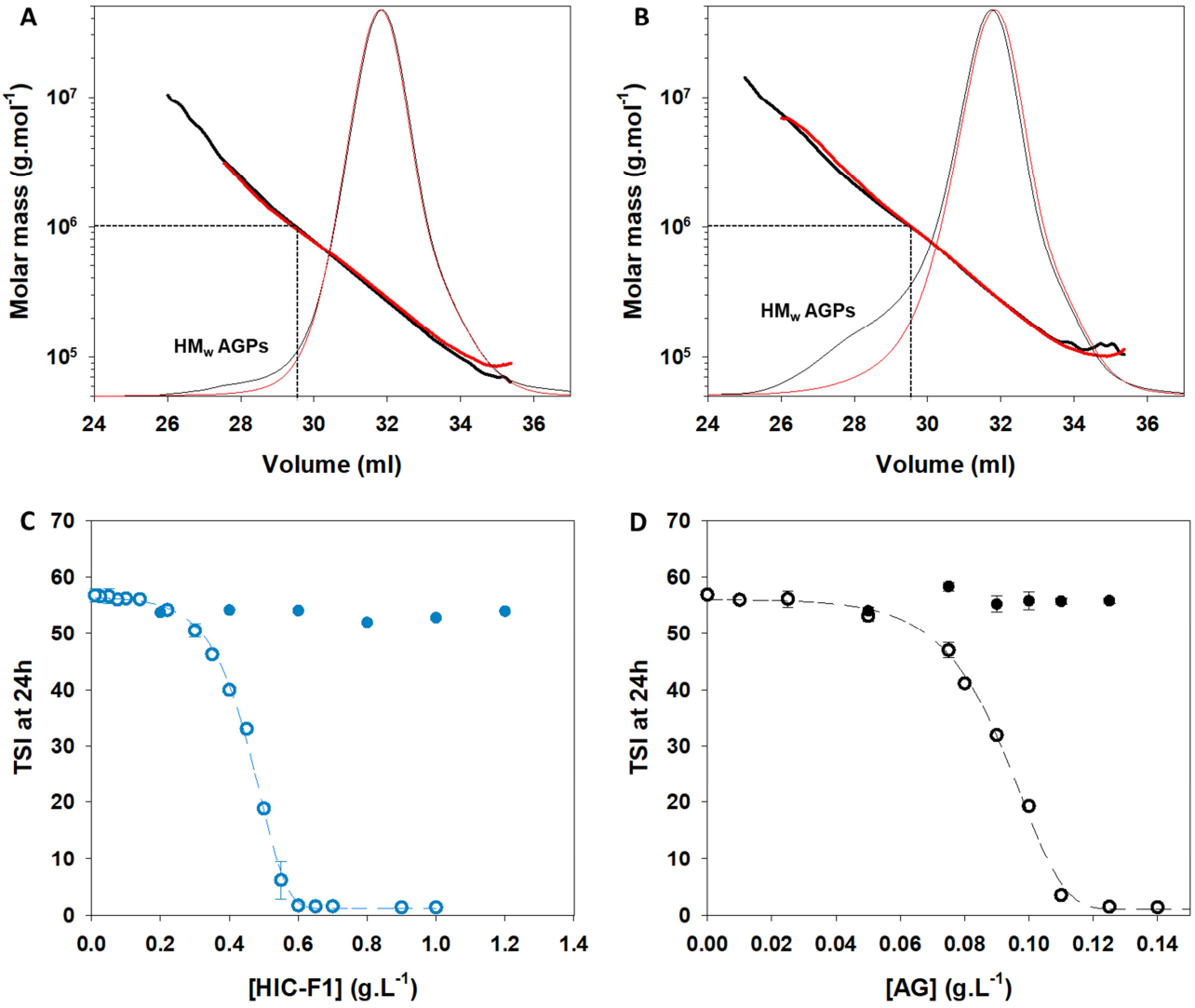
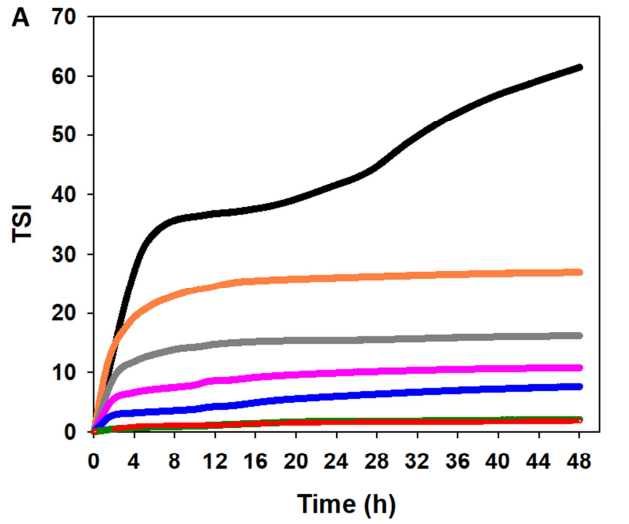
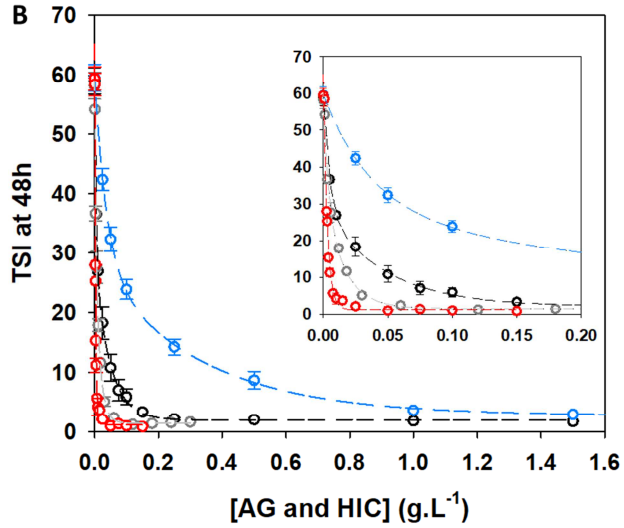
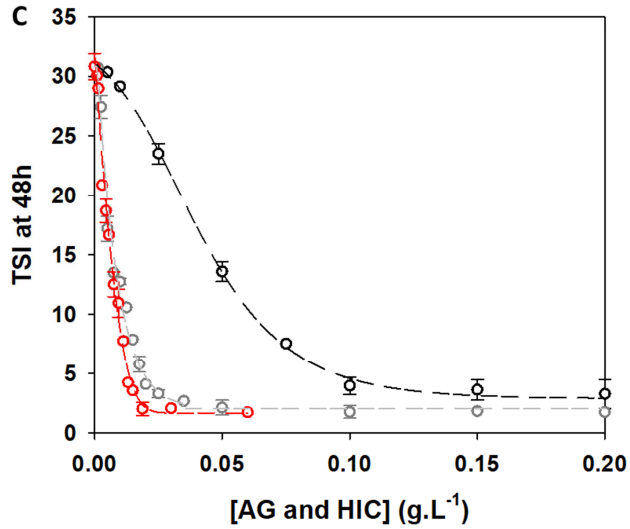


Figure 7. (A) Colloid stability kinetic of hydro-alcoholic – grape marc solutions according to A. *senegal* gum (AG) concentration at 10°C. The concentrations of A. *senegal* gum were 0 (●), 0.01 (●), 0.025 (●), 0.05 (●), 0.1 (●) and 0.5 (●) $g.L^{-1}$. The colloidal stability kinetic of the hydro-alcoholic – grape marc solution at 25°C without A. *senegal* gum is shown as a control (●) (B) Colloidal stability curves of hydro-alcoholic – grape marc solution in presence of A. *senegal* gum (○), HIC-F1 (○), HIC-F2 (○) and HIC-F3 (○) fractions after 48h of kinetic at 10°C. (C) Colloidal stability curves of a young red wine in presence of A. *senegal* gum (○), HIC-F2 (○) and HIC-F3 (○) fractions after 48h of kinetic at 10°C. The lines (figures 7B and 7C) are shown to guide the eyes. The inset figure is a zoom of the left part. The experiments were triplicated.





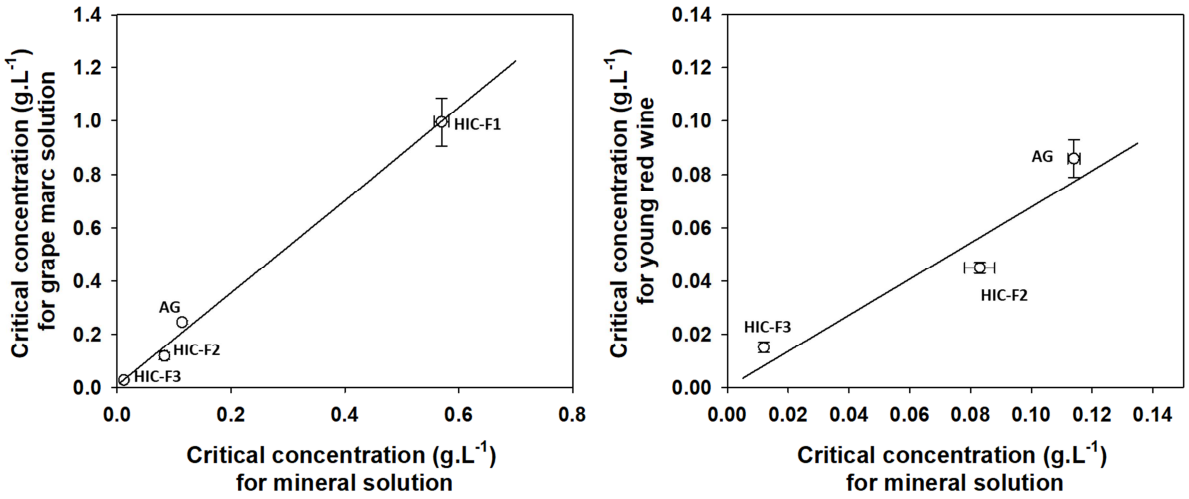


804

805

806 Figure 8. Relationship between the critical concentrations of A. *senegal* gum (AG) and its
807 HIC-fractions determined in hydro-alcoholic – mineral solution and those determined in
808 hydro-alcoholic grape marc solution (A) and young red wine (B). The experiments were
809 triplicated.

810



811

812

813

814

815

816

817

818

819

820

821

822

823

824

825

826 Supplementary table 1. Biochemical and structural properties of Acacia *senegal* gum (AG),

827 and its HIC fractions.

828

	AG	HIC-F1	HIC-F2	HIC-F3
Total dry matter ($mg.g^{-1}$)	893.4	921.6	926.2	921.9
Sugars ($mg.g^{-1}$)	944.4	961.3	918.3	813.0
Galactose	363.6	374.9	315.9	270.7
Arabinose	281.4	257.6	326.9	311.4
Rhamnose	120.9	120.2	125.8	113.0
Glucuronic acid	168.1	195.1	143.3	111.4
4-O-Me-Glucuronic acid	9.4	13.5	5.5	5.7
Proteins ($mg.g^{-1}$)	21.5	4.9	63.1	137.7
Ash ($mg.g^{-1}$)	34.1	30.5	19.3	49.3
M_w ($g.mol^{-1}$)	6.8×10^5	3.5×10^5	1.5×10^6	1.6×10^6
High M_w content (%) [a]	14	3	73	56

829

830 [a] The high M_w corresponded to macromolecules with a M_w upper than 10^6 $g.mol^{-1}$.

831

832

Highlights.

- AGPs from Acacia *senegal* gum prevent the coloring matter precipitation
- The more AGPs are rich in proteins, the more their stabilizing efficiency are
- Stabilizing properties of AGPs are correlated in “synthetic” solutions and red wine
- In “synthetic” mineral solution, AGPs avoid the precipitation by Ca^{2+} binding