Aspalathin from Rooibos (Aspalathus linearis): A Bioactive C-glucosyl Dihydrochalcone with Potential to Target the Metabolic Syndrome

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Key words
Aspalathus linearis, Fabaceae, aspalathin, metabolic syndrome, oxidative stress, molecular mechanism, bioavailability, herb-drug interactions

ABSTRACT
Aspalathin is a C-glucosyl dihydrochalcone that is abundantly present in Aspalathus linearis. This endemic South African plant, belonging to the Cape Floristic region, is normally used for production of rooibos, a herbal tea. Aspalathin was valued initially only as precursor in the formation of the characteristic red-brown colour of “fermented” rooibos, but the hype about the potential role of natural antioxidants to alleviate oxidative stress, shifted interest in aspalathin to its antioxidant properties and subsequently, its potential role to improve metabolic syndrome, a disease condition interrelated with oxidative stress. The potential use of aspalathin or aspalathin-rich rooibos extracts as a condition-specific nutraceutical is hampered by the limited supply of green rooibos (i.e., “unfermented” plant material) and low levels in “fermented” rooibos, providing incentive for its synthesis. In vitro and in vivo studies relating to the metabolic activity of aspalathin are discussed and cellular mechanisms by which aspalathin improves glucose and lipid metabolism are proposed. Other aspects covered in this review, which are relevant in view of the potential use of aspalathin as an adjunctive therapy, include its poor stability and bioavailability, as well as potential adverse herb-drug interactions, in particular interference with the metabolism of certain commonly prescribed chronic medications for hyperglycaemia and dyslipidaemia.

Introduction
Mounting evidence that dietary polyphenols may modulate dysglycaemia, a major metabolic aberration associated with the development of type 2 diabetes, is rooted in the demonstration by Von Mering in 1886 that high doses of the dihydrochalcone phloridzin (2′-β-D-glucopyranosyloxyphloretin) reduced glucose reabsorption from the renal filtrate, causing glucosuria in dogs and later also confirmed in humans [1]. This earned phloridzin the distinction as “the only compound known to have a definite action in man” as stated in a book chapter on the economic importance of flavonoid compounds in foodstuffs, published in 1962 [2]. Since the discovery of Von Mering, studies on phloridzin have progressed to the development of C-glucosyl analogues, not only with longer pharmacokinetic half-lives and duration of action than O-glucosides, but with high selectivity for SGLT2 over SGLT1 (re-
A recent review of the health effects of phloretin, the aglycone of phloridzin, stated that to date, about 200 dihydrochalcones, isolated from more than 300 plant families, have been identified [12]. *Aspalathus linearis* (Burm.f.) Dahlg., one of more than 270 species of the genus *Aspalathus* (Family Fabaceae, Tribe Crotalariaeae) and endemic to the Cape Floristic Region [13, 14], is the natural and, until recently, only reported source of aspalathin. A closely related species, *Aspalathus pendula* R. Dahlgren, was recently also shown to contain aspalathin [15]. *A. linearis* is an erect spreading shrub up to 2 m high with green, needle-like leaves on straight, slender branches. The leaves (15–60 mm long; up to 1 mm thick) are densely clustered without stalks and stipules. The small, yellow flowers of the cultivated type appear in spring to early summer and are solitary or arranged in groups at the tips of branches. The fruit is a small lance-shaped pod usually containing one or two hard seeds. The species is exceptionally polymorphic with ecotypes differing in morphology, fire survival strategy (re-seeding or resprouting), geographical distribution, and phenolic composition [16–19]. Van Heerden et al. [19], investigating the phenolic profile of ecotypes of *A. linearis*, as well as that of the closely related *A. pendula*, did not detect aspalathin in the collected *A. pendula* samples, but demonstrated it to be the major compound in most *A. linearis* populations, including the cultivated type. Recently, however, Stander et al. [15], using state-of-the-art mass spectrometric techniques, could detect aspalathin in two populations of *A. pendula*. They concluded that *A. linearis* and *A. pendula* are very closely related species, probably the same species.
A. pendula produce similar combinations of main compounds with no diagnostic patterns. Only the selected and improved Nortier type (one of the Red Rocklands types) is used for commercial cultivation of rooibos tea (Fig. 1) in the Cederberg region of the Western Cape.

The aspalathin content of the plant material is known to vary substantially between plants from the same plantation [20,21] due to the fact that the plants are propagated from open-pollinated seeds [22]. Fig. 2 depicts the variation in the aspalathin content of the leaves of individual plants, harvested on the same date from the same plantation. The largest number of leaf samples contained ca. 8% aspalathin (dry weight basis). Table 2 summarises ranges and means for aspalathin content in various types of plant material, extracts, and infusions. Aspalathin is present in substantially higher amounts in the leaves (6–13%) [21] than the stems (0.16–0.78%) (Fig. 3) and thus also the whole dried shoots (4–10%) [20]. Rooibos produced in the tradi-

### Table 1 Physical properties of aspalathin.

<table>
<thead>
<tr>
<th>Property (units)</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td></td>
<td><img src="image" alt="Structure" /></td>
</tr>
<tr>
<td>IUPAC name</td>
<td>3-(3,4-Dihydroxyphenyl)-1-[(2,4,6-trihydroxy-3-[25,3R,4R,5S,6R]-3,4,5-trihydroxy-6-(hydroxymethyl)tetrahydro-2H-pyran-2-yl)phenyl]propan-1-one</td>
<td>[7]</td>
</tr>
<tr>
<td>Molecular formula</td>
<td>C21H24O11</td>
<td>[7, 8]</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>452.412</td>
<td>[7, 8]</td>
</tr>
<tr>
<td>Melting point</td>
<td>152–154°C</td>
<td>[9]</td>
</tr>
<tr>
<td>Polar surface area (Å²)</td>
<td>208</td>
<td>[7]</td>
</tr>
<tr>
<td>Log P (predicted)</td>
<td>2.07</td>
<td>[8]</td>
</tr>
<tr>
<td>Log D (pH 7.4) (experimental)</td>
<td>0.13</td>
<td>[10]</td>
</tr>
<tr>
<td>Log D (pH 5.5) (experimental)</td>
<td>−0.347</td>
<td>[11]</td>
</tr>
<tr>
<td>H bond acceptors</td>
<td>11</td>
<td>[7, 8]</td>
</tr>
<tr>
<td>H bond donors</td>
<td>9</td>
<td>[7, 8]</td>
</tr>
<tr>
<td>Freely rotating bonds</td>
<td>6</td>
<td>[7, 8]</td>
</tr>
<tr>
<td>“Rule of 5” violations</td>
<td>2</td>
<td>[8]</td>
</tr>
<tr>
<td>Solubility at pH 2 (µM)</td>
<td>153</td>
<td>[10]</td>
</tr>
<tr>
<td>Solubility at pH 6.5 (µM)</td>
<td>123</td>
<td>[10]</td>
</tr>
<tr>
<td>Solubility in FaSSIF at pH 6.5 (µM)</td>
<td>119</td>
<td>[10]</td>
</tr>
</tbody>
</table>
nolic content of a cup of fermented rooibos tea and extracts used in biological studies resulted in the development of a variety of methods [32–36]. The method developed by Beelders et al. [34] to characterise the phenolic content of infusions of fermented rooibos could, besides aspalathin, quantify the content of the dihydrochalcone nothofagin, the phenolic acid ferulic acid, and (Z)-2-(β-D-glucopyranosyl)-3-phenylpropiolic acid, an enolic glucoside of phenylpyruvic acid, as well as the major flavones and flavonols. Quantitative data for rutin and quercetin-3-O-robinobioside indicate that these compounds most likely co-eluted when using previous methods. Comprehensive analysis of the phenolic composition of fermented rooibos is problematic since a number of critical peak pairs need to be resolved. The most recent method was shown to be suitable for quantification of the flavanone oxidation products of aspalathin [37]. A need to screen large numbers of green rooibos samples led to the development of a rapid HPLC method to quantify aspalathin, nothofagin, iso-orientin, and orientin [30]. Kazuno et al. [38] used a triple quadrupole MS detector in a selected reaction monitoring mode to quantify a number of rooibos phenolic compounds, including aspalathin. The use of mass spectrometric detection increases the sensitivity and specificity of the method. The suitability of capillary zone electrophoresis for quantification of aspalathin and other phenolic compounds in rooibos was investigated by Arries et al. [39]. It was deemed less sensitive and a smaller number of compounds could be quantified with suitable reproducibility, but has potential as a rapid, inexpensive alternative method, especially for quantification of the major compounds.

Physical and chemical properties

Aspalathin (PubChem CID: 11282394; Chemspider ID: 9457391) is a natural C-glucosyl dihydrochalcone (3′-β-D-glucopyranosyl-2′,3,4,4′,6′-pentahydroxydihydrochalcone) with the molecular formula C_{21}H_{26}O_{11} (MW 452.412 g/mol) (Table 1) [7, 8]. The compound was first described by Koeppe [40, 41], originally designated “compound J”, and tentatively identified as a flavanone based on its chromatographic properties, chromogenic reactions with a variety of reagents, UV-Vis and infrared spectra, spectral shifts, and hydrolysis products. Aspalathin was eventually identified as a dihydrochalcone based on its oxidation products [9] and NMR data acquired at 60 MHz [42]. Renewed interest in the phe-

### Table 2 Aspalathin content and variation in various types of plant material (PM), extracts, and infusions.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>N</th>
<th>Range (mean)</th>
<th>Units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dried leaves</td>
<td>54</td>
<td>6.0–13.5 (9.7)</td>
<td>g/100 g PM</td>
<td>[21]</td>
</tr>
<tr>
<td>Stems</td>
<td>6</td>
<td>0.16–0.78 (0.33)</td>
<td>g/100 g PM</td>
<td></td>
</tr>
<tr>
<td>Whole dried shoots</td>
<td>97</td>
<td>3.8–9.7 (6.6)</td>
<td>g/100 g PM</td>
<td>[20]</td>
</tr>
<tr>
<td>Green product</td>
<td>47</td>
<td>2.5–4.5 (3.6)</td>
<td>g/100 g PM</td>
<td>[25]</td>
</tr>
<tr>
<td>Fermented product</td>
<td>89</td>
<td>0.02–1.2 (0.3)</td>
<td>g/100 g PM</td>
<td>[20]</td>
</tr>
<tr>
<td>Green hot water extract</td>
<td>47</td>
<td>8.1–12.3 (10.5)</td>
<td>g/100 g extract</td>
<td>[25]</td>
</tr>
<tr>
<td>Fermented hot water extract</td>
<td>74</td>
<td>0.16–1.52 (0.58)</td>
<td>g/100 g extract</td>
<td>[26]</td>
</tr>
<tr>
<td>Green infusion</td>
<td>10</td>
<td>78–251 (158)</td>
<td>mg/L</td>
<td>[28]</td>
</tr>
<tr>
<td>Fermented infusion</td>
<td>114</td>
<td>nd–15.7 (5.8)</td>
<td>mg/L</td>
<td>[29]</td>
</tr>
</tbody>
</table>
nolic composition of rooibos more than 30 years after the first isolation of aspalathin resulted in full elucidation of its structure via $^1$H NMR data acquired at 300 MHz [43].

Aspalathin is readily soluble in water and polar solvents, but insoluble in nonpolar solvents. Other physical properties, relating specifically to bioavailability, are discussed later. It is highly susceptible to oxidation in the presence of oxygen in solution [30, 42, 44–47] and rooibos plant material [31]. In the latter matrix, enzymes catalyse the reaction (unpublished data). Bruising of the fresh leaves results in rapid browning. The oxidation products identified in solution are shown in ▶ Fig. 4. Oxidation commences by cyclisation of aspalathin (1) to form the diastereomeric flavanone mixture (5S)- and (5R)-6-β-D-glucopyranosyleriodictyol (2 and 3) as major products and the diastereomeric mixture (5S)- and (5R)-8-β-D-glucopyranosyleriodictyol (4 and 5) as minor products. The flavanones 2 and 3 are oxidised to form the flavone isoorientin (6). The latter compound is susceptible to a Wessely-Moser-type rearrangement, i.e., hydrolysis of the enolic ether functionality and subsequent recycylation of a 1,3-diketo intermediate via the alternative o-hydroxy group, to form orientin (7) irreversibly, although the major oxidation products are unidentified brown material. The flavanones 4 and 5 are not oxidised directly to orientin (7), but these compounds are postulated to be reversibly transformed into the thermodynamically more stable flavanones 2 and 3 via the intermediate quinone methide. Further oxidation products of aspalathin include 8 and 9 atropo-diastereomeric phenols formed via phenol oxidative A- to B-ring coupling. These dimers can undergo a second phenol oxidative coupling to form the dimer 10. The 9H-fluorene 11 is postulated to form via a two-step oxidation process. The dimers are also susceptible to further oxidation into unidentified brown products. A study to investigate the formation of the brown colour upon oxidation identified aspalathin as the most important substrate for the formation of coloured products [47].

Degradation of aspalathin is pH dependent (▶ Fig. 5). Aspalathin stability is highest at a low pH and substantial degradation (47%) occurs over 24 h at pH 7 in a citric acid-phosphate buffer at room temperature (▶ Fig. 5A) [30]. Other factors such as buffer type, ascorbic acid, and environment also have an effect (▶ Fig. 5B, C; unpublished results). A phosphate buffer (pH 7.4) without citric acid showed up to 97% degradation over 24 h at room temperature (▶ Fig. 5B), indicating that citric acid has a protective effect. The metal chelating properties of citric acid may be a contributing factor. Ascorbic acid, on the other hand, was able to completely prevent aspalathin degradation in a phosphate buffer (pH 7.4) over 24 h at room temperature (▶ Fig. 5B).
For a study on the permeability of aspalathin in a Caco-2 cell model [10], the stability of aspalathin as a pure compound and when present in an aspalathin-rich green rooibos extract was determined under cell culture conditions (pH 7.4) over 2 h in HBSS (Fig. 5C). Under these conditions, 14 and 27% degradation of the compound occurred when pure aspalathin and aspalathin-rich extract, respectively, were tested. At pH 6 under cell culture conditions, the aspalathin concentration slightly increased, which was attributed to evaporation of the medium.

Antioxidant and pro-oxidant properties

Research interest in natural phenolic antioxidants began to escalate from 1995 as evidenced by the increase in the number of papers published [49]. Prior to this date, Japanese interest in rooibos produced a few papers relating to the free radical scavenging ability of fermented rooibos (as reviewed by Joubert et al. [50]). The latter research led to the association of rooibos with its anti-oxidant activity of aspalathin was compared to that of isoquercitrin, a quercetin glucoside, in the Rancimat and LDL oxidation assays. Aspalathin showed higher and lower inhibitory activity than isoquercitrin in these assays, respectively. In the β-carotene bleaching and Fe(II)-induced microsomal lipid peroxidation assays, aspalathin showed lower activity than quercetin [54, 55].

The emphasis to obtain a process for chemical synthesis of aspalathin stems from its relatively low content in the bulk of rooibos material, especially green rooibos. Synthesis of aspalathin would be postulated to play a role in the prevention of UVB-induced skin carcinogenesis [58]. With regard to lipid peroxidation, the activity of aspalathin was compared to that of isoquercitrin, a quercetin glucoside, in the Rancimat and LDL oxidation assays. Aspalathin showed higher and lower inhibitory activity than isoquercitrin in these assays, respectively. In the β-carotene bleaching and Fe(II)-induced microsomal lipid peroxidation assays, aspalathin showed lower activity than quercetin [54, 55].

The in vitro antioxidant activity of aspalathin (Table 3) has been assessed in a variety of assays including radical scavenging and lipid peroxidation assays [52–56]. Aspalathin generally had lower antioxidant activity than the well-known radical scavenger quercetin [52, 54, 55, 57], although similar activity was reported in the ABTS radical cation [54, 56], Freny’s radical [56] and superoxide radical anion [52] scavenging assays. Aspalathin also showed pro-oxidant activity in the deoxyribose assay [53]. In this assay, hydroxyl radicals are generated in a Fenton reaction model system containing FeCl3-EDTA and H2O2, where aspalathin was able to reduce Fe3+ to Fe2+, thereby increasing formation of hydroxyl radicals. In this system, potent antioxidants act as potent pro-oxidants. In a recent paper, the dual antioxidant and/or pro-oxidant role of rooibos polyphenol constituents, in particular aspalathin, was postulated to play a role in the prevention of UVB-induced skin carcinogenesis [58]. With regard to lipid peroxidation, the activity of aspalathin was compared to that of isoquercitrin, a quercetin glucoside, in the Rancimat and LDL oxidation assays. Aspalathin showed higher and lower inhibitory activity than isoquercitrin in these assays, respectively. In the β-carotene bleaching and Fe(II)-induced microsomal lipid peroxidation assays, aspalathin showed lower activity than quercetin [54, 55].

The emphasis to obtain a process for chemical synthesis of aspalathin stems from its relatively low content in the bulk of rooibos produced (i.e., fermented rooibos tea), the cost and challenge of isolation from the plant material, and the limited supply of plant material, especially green rooibos. Synthesis of aspalathin would represent a sustainable option if economically feasible. An eight-step process using tri-O-benzylglucal, tri-O-benzylphloroglucinol, and 3,4-bis(benzyloxy)phenylacetylene as starting materials was reported by Yepremyan et al. [60]. This process involved a stereoselective Lewis acid-promoted coupling of 1,2-di-O-acyl-3,4,6-tri-O-benzylglucose with tri-O-benzylphloroglucinol, leading to the chemical and potential biocatalytic syntheses.
corresponding β-D-glucopyranosylflorogluconin derivative that was subsequently transformed to aspalathin. Nothofagin was also synthesised in a similar manner. Since the aforementioned synthetic protocol resulted in a low yield (20%), an alternative sequence was developed by Van der Westhuizen and coworkers \(\text{Fig. 6}\) [61]. Glucosylation of the di-O-benzylacetophenone 14 with the α-fluoroglucosyl derivative 13 under Lewis acid-catalysis afforded the α-glucopyranosylxylo analogue 15 in an 86 % yield. Increasing the temperature from –40 to –15°C permitted a facile BF3-catalysed rearrangement to the β-glucopyranosyl derivative 16 in an 84% yield. Aldol condensation of 16 with 3,4-dibenzyl-oxybenzaldehyde 17 afforded the protected chalcone 18 (96% yield), which upon hydrogenation gave aspalathin in an 80% overall yield. Based on the excellent overall yield and its scalability potential, the process was subsequently patented [62]. Recently, a number of C-glycosyl chalcone analogues of aspalathin were synthesised by a simple three-step process [63]. These analogues displayed good DPPH radical scavenging activity and inhibited proliferation of liver and breast cancer cells.

**Table 3** Summary of in vitro antioxidant and pro-oxidant activity of aspalathin.

<table>
<thead>
<tr>
<th>Assay</th>
<th>Antioxidant mechanism</th>
<th>Antioxidant measure</th>
<th>Relative activity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPPH radical scavenging</td>
<td>Synthetic radical scavenging</td>
<td>% Inhibition</td>
<td>Higher activity than BHT, BHA, α-tocopherol, luteolin, vitexin, rutin, and phenolic acids Lower activity than quercetin, catechin, and isoquercitrin</td>
<td>[55]</td>
</tr>
<tr>
<td>DPPH radical scavenging</td>
<td>Synthetic radical scavenging</td>
<td>% Inhibition</td>
<td>Higher activity than isoorientin, catechin, epicatechin, rutin, Trolox, vitexin, and chrysoeriol Similar activity to orientin, luteolin, isoquercitrin, and propyl gallate Lower activity than quercetin and procyanidin B1, B2, B3, and B4</td>
<td>[52]</td>
</tr>
<tr>
<td>ABTS radical cation scavenging</td>
<td>Synthetic radical scavenging</td>
<td>IC50</td>
<td>Higher activity than Trolox, catechin, isoorientin, luteolin, chrysoeriol, rutin, isoquercitrin, hyperoside, nothofagin, vitexin, and isovertexin Similar activity to quercetin and epigallocatechin gallate</td>
<td>[54]</td>
</tr>
<tr>
<td>ABTS radical cation scavenging</td>
<td>Synthetic radical scavenging</td>
<td>TEAC</td>
<td>Higher activity than nothofagin, isoorientin, orientin, isovitexin, vitexin, (S)- and (R)-6-β-D-glucopyranosyleryiodictyol, rutin, isoquercitrin, and hyperoside Similar activity to quercetin</td>
<td>[56]</td>
</tr>
<tr>
<td>Fremy’s radical scavenging</td>
<td>Synthetic radical scavenging</td>
<td>Mole radicals scavenged per mole compound</td>
<td>Higher activity than nothofagin, isoorientin, orientin, isovitexin, vitexin, (S)- and (R)-6-β-D-glucopyranosyleryiodictyol, rutin, isoquercitrin, and hyperoside Similar activity to quercetin</td>
<td>[56]</td>
</tr>
<tr>
<td>Superoxide radical scavenging</td>
<td>Oxygen radical scavenging</td>
<td>% Inhibition</td>
<td>Higher activity than orientin, luteolin, isoquercitrin, isoorientin, catechin, epicatechin, rutin, Trolox, vitexin, and chrysoeriol Similar activity to quercetin Lower activity than propyl gallate and procyanidin B1, B2, B3, and B4</td>
<td>[52]</td>
</tr>
<tr>
<td>ORAC with fluorescein</td>
<td>Peroxyl radical scavenging</td>
<td>ORAC index</td>
<td>Higher activity than nothofagin Lower activity than quercetin, orientin, isoorientin, vitexin, isoquercitrin, and hyperoside</td>
<td>[57]</td>
</tr>
<tr>
<td>ORAC with pyrogallol red</td>
<td>Peroxyl radical scavenging</td>
<td>ORAC index</td>
<td>Higher activity than nothofagin, orientin, isoorientin, vitexin, isoquercitrin, and hyperoside Lower activity than quercetin</td>
<td>[57]</td>
</tr>
<tr>
<td>Deoxyribose degradation in Fenton system</td>
<td>Hydroxyl radical scavenging/ generation</td>
<td>TBARS vs. control</td>
<td>Pro-oxidant activity in the absence of ascorbic acid</td>
<td>[53]</td>
</tr>
<tr>
<td>Rancimat lard oxidation</td>
<td>Lipid peroxidation</td>
<td>Induction period</td>
<td>Higher activity than p-hydroxybenzoic acid, ferulic acid, and p-coumaric acid Lower activity than quercetin, BHT, α-tocopherol, catechin, luteolin, rutin, isoqueritrin, caffeic acid, and protocatechuic acid</td>
<td>[55]</td>
</tr>
<tr>
<td>Coupled β-carotene bleaching and linoleic acid oxidation</td>
<td>Lipid peroxidation</td>
<td>AAC after 120 min reaction time</td>
<td>Higher activity than catechin, vitexin, rutin, isoquercitrin, and phenolic acids Lower activity than quercetin, BHT, BHA, α-tocopherol, and luteolin</td>
<td>[55]</td>
</tr>
<tr>
<td>LDL oxidation</td>
<td>Lipid peroxidation</td>
<td>Lag time</td>
<td>Higher activity than isoorientin, orientin, nothofagin, and (S)-6-β-D-glucopyranosyleryiodictyol Lower activity than isoquercitrin</td>
<td>[56]</td>
</tr>
<tr>
<td>Fe(II)-induced microsomal lipid peroxidation</td>
<td>Lipid peroxidation</td>
<td>IC50</td>
<td>Higher activity than Trolox, orientin, isoorientin, luteolin, chrysoeriol, rutin, isoquercitrin, hyperoside, nothofagin, vitexin, and isovertexin Similar activity to catechin Lower activity than quercetin and epigallocatechin gallate</td>
<td>[54]</td>
</tr>
</tbody>
</table>
Another possibility for the synthesis of aspalathin may be the biotransformation by enzymatic C-glycosylation of the aglycone, as was achieved for nothofagin [64, 65]. A C-glycosyltransferase from rice, which was perfectly selective, was used to glucosylate phloretin using uridine diphosphate-glucose, giving an 80% yield of nothofagin [64]. In further work, the same group increased the efficiency of conversion by complexing phloretin with β-cyclodextrin to improve its solubility [65].

De novo synthesis of nothofagin and a number of other related dihydrochalcones was recently accomplished using metabolically engineered *Saccharomyces cerevisiae* [66]. This was done by expressing the full-length biosynthetic pathways, consisting of between four and nine genes, in the microbial host. Although the authors note that the process is not yet economically viable, metabolically engineered microbes have great potential for targeted sustainable production of high-value phenolic compounds such as aspalathin.

**Bioavailability**

Aspalathin, normally ingested by drinking rooibos or consuming food supplemented with rooibos extract, requires absorption through the gut into the blood stream to reach the systemic site of action in adequate concentrations to be bioefficient, apart from its beneficial gastrointestinal luminal effects. Considering that various physical properties of aspalathin (Table 2) related to membrane permeability fail to meet various criteria, limited absorption is to be expected. Whilst its molecular weight and log P value do not exceed the limits of 500 and 5, respectively, the number of H-bond donors and acceptors violate Lipinski’s “Rule of 5” [67]. The hydrophilic nature of aspalathin not only indicates poor permeability for gastrointestinal penetration, but also susceptibility to renal clearance [68]. Additionally, the polar surface area of aspalathin exceeds 140 Å², indicating a high probability of poor oral bioavailability [69].

Low membrane permeability of aspalathin has been reported in Caco-2 monolayer cell model studies. Relevant details of these studies are summarised in Table 4. Notably, Huang et al. [11] found that aspalathin absorption increased when present in green rooibos extract as opposed to the pure compound, indicating that other plant components present in the extract may assist in its transport across the membrane. In contrast, Bowles et al. [10] found absorption of pure aspalathin to be similar to that when present in green rooibos extract. Experimental differences may account for this disparity in results, in particular the substantially higher aspalathin concentration, as well as the higher permeability of the monolayer used by Huang et al. [11]. Courts and Williamson [70] postulated that the passive diffusion of aspalathin is most likely responsible for its absorption across the intestinal epithelial monolayer. Insight into the mechanism of aspalathin transport, using the Caco-2 monolayer cell model, was gained from the study by Bowles et al. [10]. Following inhibition of aspalathin transport in the presence of a high glucose concentration (20.5 mM), the role of active glucose transporters such as SGLT1 and GLUT2 was investigated by performing experiments in the presence and absence of SGLT1 (phloridzin), GLUT2 (phloretin), and efflux (Pg) (verapamil) inhibitors. No effect on aspalathin transport was observed, leading to the conclusion that aspalathin is transported paracellularly, especially given its physical characteristics. Transport of aspalathin across the intestinal epithelial monolayer occurred without evidence of deglucosylation [70] or formation of other metabolites [10].

In vitro phase II metabolism of aspalathin with microsomal and cytosolic subcellular rat liver fractions and added cofactors produced two glucuronidated and one sulphated metabolite [71]. Methylation of aspalathin was demonstrated when treated with human liver and intestinal cytosolic fractions, following the addition of the cofactor [72]. Conjugates of aspalathin with glucuronic acid, sulphate, a methyl group, or a combination were detected in animal and human urine [10, 33, 36, 72, 73]. Deglucosylation of aspalathin is thus not a prerequisite for its absorption. Traces of methyl conjugates were found in the plasma of Vervet monkeys after being fed a single bolus containing green rooibos extract delivering 25 mg aspalathin per kg body weight [28]. Unconjugated aspalathin was detected in human plasma after ingesting a green rooibos beverage containing 287 mg aspalathin (Table 5). In all of the in vivo studies, except the mouse study, aspalathin was in-
gested as part of a rooibos extract, either mixed into the feed of the animals or consumed as a rooibos beverage by human subjects (Table 5). Major outcomes of these studies were that aspalathin metabolites reached maximum concentration in the plasma in 3 h or less [33] and that only a small quantity of the ingested amount was bioavailable [33, 36, 72].

Of interest is the presence of the conjugated aspalathin aglycone, observed in mouse [10] and human [33] urine. The resistance of the C-C bond to the action of lactase phloridzin hydrolase, present in the brush-border of the small intestinal epithelial cells, as well as the action of cytosolic \(\beta\)-glucosidase [74], requires liberation of the aglycone by colonic microflora. Human colonic bacteria able to hydrolyse the C-C bond have been identified for a number of C-glucosyl compounds [75–77]. *Eubacterium cellulosolvens*, isolated from mice, are able to deglucosylate orientin and isoorientin [78]. Using oxidation products of aspalathin as a starting point and outcomes of studies on the anaerobic catabolism of these flavones, Muller et al. [28] proposed a microbial biotransformation pathway for aspalathin, ultimately leading to the formation of dihydrocaffeic acid and organic acids in the colon.

**Rising burden of metabolic syndrome and preventative potential of aspalathin**

The metabolic syndrome describes a cluster of metabolic anomalies that underlie the development of serious metabolic disease such as type 2 diabetes, obesity, and cardiovascular disease, contributing to the rising burden of noncommunicable diseases [79]. Perturbations of glucose and lipid metabolism as a result of insulin resistance play a major role in the development of the metabolic syndrome. Individuals with this condition exhibit multiple risk factors including elevated fasting plasma glucose, high serum triglycerides, and high blood pressure, which increase the probability of developing cardiovascular complications [80]. Urbanisation with accompanying lifestyle changes, namely, excessive energy intake and lack of physical activity, contributes to these metabolic diseases [79]. Current global estimates show that more than 2 billion children and adults are overweight or obese, whereas a total of 107.7 million children and 603.7 million adults were recorded to be obese in 2015 [81]. Furthermore, the International Diabetes Federation has reported that 415 million adults have diabetes at present and this number is expected to rise to 642 million by 2040 [82]. Cardiovascular diseases, major comorbidities of type 2 diabetes, greatly contribute to global mortality [79]. In addition to cardiovascular diseases, the metabolic syndrome increases the risk of organ damage to the liver (nonalcoholic fatty liver disease), muscle (muscle deterioration), and pancreas (pancreatic \(\beta\)-cell dysfunction) [83, 84]. The generation of excessive oxidative stress, a consequence of depleted antioxidant systems due to the overproduction of ROS, and accelerated inflammation driven by elevated proinflammatory cytokine production, are both implicated in metabolic syndrome-induced organ damage [85]. Nevertheless, there is an increase in evidence that dietary interventions may reduce oxidative stress and inflammation associated with the metabolic syndrome, thereby decreasing cardiovascular risk [86, 87]. For example, antioxidant transcriptional factors such as Nrf2, as well as its associated downstream target genes including those coding for GSH, have emerged as essential targets in the amelioration of oxidative stress-induced cardiovascular and liver damage [88–90]. Similarly, effective modulation of protein kinases such as JNK, IKK, ERKs, and AMPK by certain natural products has been correlated with a reduced inflammatory response and cell damage [91–93]. Evidence demonstrating the ameliorative potential of aspalathin against the metabolic syndrome and its associated complications is attracting a lot of interest. The following sections provide a brief overview of the metabolic processes involved in altered glucose and lipid metabolism, leading to exacerbated oxidative stress and inflammatory-induced cell damage. A separate section deals specifically with the protective potential of aspalathin and its possible interference with the metabolism of hypoglycaemic and hypocholesterolaemic drugs.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Concentration(^1)</th>
<th>(P_{app} \times 10^{-6})</th>
<th>% Passage</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green rooibos extract in DPBS with calcium and magnesium (pH 7.4)</td>
<td>1 mg/mL (0.43 mM)</td>
<td>4 ± 0.42</td>
<td>[11]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 mg/mL (2.15 mM)</td>
<td>3.49 ± 1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 mg/mL (4.29 mM)</td>
<td>20.93 ± 3.61</td>
<td>~ 100%</td>
<td></td>
</tr>
<tr>
<td>Aspalathin in DPBS with calcium and magnesium (pH 7.4)</td>
<td>0.2 mg/mL (0.44 mM)</td>
<td>0.91 ± 0.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 mg/mL (2.21 mM)</td>
<td>2.48 ± 0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 mg/mL (4.42 mM)</td>
<td>15.34 ± 1.66</td>
<td>79%</td>
<td></td>
</tr>
<tr>
<td>Aspalathin in HBSS (pH 6.0)(^2)</td>
<td>1 (\mu)M</td>
<td>2.28 ± 0.09</td>
<td></td>
<td>[10]</td>
</tr>
<tr>
<td></td>
<td>150 (\mu)M</td>
<td>1.73 ± 0.97</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Aspalathin in HBSS (with high glucose; 20.5 mM; pH 6.0)</td>
<td>150 (\mu)M</td>
<td>0.29 ± 0.08</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Green rooibos extract in HBSS (pH 6.0)</td>
<td>0.38 mg/mL (153 (\mu)M)</td>
<td>2.00 ± 1.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enriched green rooibos fraction in HBSS (pH 6.0)</td>
<td>0.15 mg/mL (149 (\mu)M)</td>
<td>2.11 ± 0.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)Extract concentration in mg/mL with molar concentration of aspalathin; \(^2\)molar concentrations > 150 \(\mu\)M were cytotoxic to Caco-2 cells.
Metabolic syndrome and glucose metabolism

Disturbances in glucose metabolism remain central to the etiology of metabolic syndrome. In both the fed and fasted state, glucose-induced insulin secretion is tightly controlled, and disturbances in insulin action cause an imbalance between glucose uptake and consumption [94]. In the liver, insulin action promotes lipogenesis and glycogen synthesis, while lipolysis and glycolysis are inhibited [94]. Peripheral glucose absorption and usage are stimulated by insulin in adipose and muscle tissue. Insulin resistance dysregulates these processes, resulting in increased blood glucose levels with associated lipid accumulation [95].

Insulin action is mediated through the phosphorylation of various signalling cascades, culminating in glucose uptake into the cell. Simply put, activation of PI3K/AKT by IRS-1 phosphorylates GSK3-β and initiates GLUT4 translocation from the cytosol to the cell membrane [96]. Both PI3K and AKT are crucial kinases that regulate GLUT4 translocation and have subsequently gathered significant interest as possible drug targets for treating the metabolic syndrome [94, 96]. Conversely, in an obese or type 2 diabetic state, elevated DAG and ceramide levels can activate PKC, leading to a dysregulated IRS/PI3K/AKT cascade that suppresses GLUT4-mediated glucose uptake in muscle and adipose tissues, as is observed in AKT knockout mice [97].

Although the PI3K/AKT signalling pathway is essential in the regulation of insulin-stimulated glucose uptake, glucose can also be regulated by phosphorylated AMPK in an insulin-independent manner [92]. AMPK is a major energy sensor that plays a critical role in cellular homeostasis and has been widely studied as a possible target to improve insulin resistance [98]. Through its maintenance of energy consumption, AMPK has contributed significantly to the modulation of various cellular processes, including cell growth, autophagy, and glucose metabolism [98]. For the latter, it is postulated that upon activation, AMPK promotes GLUT4 translocation to the cell membrane, resulting in increased glucose uptake in skeletal muscle and adipose tissue [99, 100]. Metformin, a biguanide class of oral antidiabetic, mediates its anti-diabetic actions by indirectly activating AMPK [101]. However, contradicting evidence also shows that activation of AMPK in a diabetic heart can contribute to the inhibition of glucose utilisation, while abnormally enhancing fatty acid oxidation that can lead to accelerated myocardial apoptosis [102–104]. Thus, in addition to the modulation of PI3K/AKT signalling, optimal regulation of AMPK remains
essential in promoting glucose uptake, reversing insulin resistance, and attenuating metabolic disease-associated complications such as oxidative stress and inflammation [98, 103].

Metabolic syndrome and lipid metabolism
Lipid metabolism can be defined as the synthesis or break down of fats for energy, a process that plays a major role in normal body function, as well as the aetiology of metabolic syndrome [105]. Fatty acids are major components of triglycerides and can either be absorbed through the ingestion of food or synthesised by adipocytes or hepatocytes from carbohydrate precursors such as acetyl-CoA [105]. This process begins in the intestine where triglycerides are degraded by pancreatic lipases and bile salts into FFAs, where they, together with cholesterol molecules, are packed into chylomicrons, which are transported within the lymphatic and circulatory system to be metabolised by cells or stored in the adipose tissue [106]. Although adipose tissue is the largest energy reserve in mammals, fats are also stored in muscle and liver tissues [106]. In muscle, fat stores are used as a substrate for fatty acid β-oxidation, whereas in the liver, fats are utilised in the synthesis of triacylglycerol for energy [106]. To obtain energy from adipocytes, fats are hydrolysed into FFAs and glycerol molecules in a process called lipolysis. These FFAs are further oxidised during mitochondrial fatty acid β-oxidation to produce acetyl-CoA, which is a major substrate required in the Krebs cycle for the production of energy in the form of ATP [105].

Fatty acid β-oxidation produces twice the amount of energy compared to carbohydrate or glucose metabolism and its dysregulation is implicated in the aetiology of the metabolic syndrome [107]. Altered β-oxidation in the muscle and liver is associated with diabetes (co-occurrence of type 2 diabetes and obesity) and an increased cardiovascular risk [108]. During the progression of obesity, increased lipogenesis and diminished β-oxidation account for augmented hepatic expression of lipogenic genes including SCD1, PPARγ, and SREBP1/2. In muscle, increased levels of long-chain FFA acyl-CoAs together with their lipid intermediate metabolites, DAG and ceramide, impede insulin action through activation of PKC [109]. Activation of PKC initiates an increased inflammatory response that augments muscle insulin resistance via activation of IRS (serine 307) (IRS\textsuperscript{Ser307}). As previously explained, this process attenuates peripheral glucose uptake and translocation of GLUT4. Nevertheless, enhanced oxidative stress appears to be one of the devastating factors associated with accelerated tissue injury as a result of impaired glucose and lipid metabolism.

Metabolic syndrome and oxidative stress
It is generally accepted that oxidative stress plays a major role in the development and exacerbation of the metabolic syndrome. The role of persistent exposure to high glucose (chronic hyperglycaemia), linked to the increased production of ROS within the disease state, is well established [110]. In diabetes, raised blood glucose levels induce various signalling pathways associated with the aggravation of oxidative stress. For example, activation of the sorbitol-aldehyde reductase pathway, a key process in the control of excess blood glucose, can cause a decrease in the reduced form of NADP, i.e., NADPH. It is well known that the NADPH cofactor plays a major role in the synthesis of GSH, an essential antioxidant that detoxifies intracellular ROS [111]. Moreover, intracellular reduction of NADPH and GSH may promote the production of nitric oxide as well as chain activation of other free radicals leading to accelerated oxidative damage [112].

Some of the well-known sources responsible for exacerbated generation of oxidative stress in many cell types include glucose autooxidation (normally identified with elevated glucose levels in a diabetic state), abnormally enhanced activity of NADPH and xanthine oxidases, and the overactivity of the mitochondrial electron transport chain [113–115]. Lipid peroxidation, which may arise as a result of oxidative degradation of lipids by increased free radical production, is a widely-reported phenomenon identified in obese individuals [116, 117]. Avci et al. [117] recently showed that enhanced lipid peroxidation inversely correlates with GSH content in individuals with metabolic syndrome. This was supported by others demonstrating that systemic markers of lipid peroxidation such as oxidised LDL and TBARS are elevated in individuals with metabolic syndrome compared to control subjects [118, 119]. Such findings have also been supported by data from animal models of metabolic syndrome with increased liver dysfunction, muscle insulin resistance, and subsequent cardiomyocyte remodelling and apoptosis [83, 84, 88].

Metabolic syndrome and inflammation
Another devastating consequence interrelated with oxidative stress that normally arises due to prolonged exposure to elevated blood glucose (hyperglycaemia) and circulating lipids (hyperlipidaemia) is the activation of inflammation. Although an inflammatory response is necessary for debridement after injury, tenacious inflammation is thought to exacerbate cell damage under various disease conditions [85]. In an obese state, a proinflammatory response results in the infiltration of macrophages into peripheral tissues, including adipose tissue and the liver as well as skeletal and heart muscle [120, 121]. In adipose tissue, the macrophage infiltration stems from excessive lipid overload of the various adipose tissue deposits, caused by adipocyte hypertrophy and hyperplasia, culminating in ischaemic tissue congestion and dysfunction [122]. In the liver, the nutrient overload causes nonalcoholic fatty liver disease [123]. Furthermore, increased lipid stores, particularly visceral adiposity, promote a low-grade systemic proinflammatory response, activating M1 macrophages (Th1 response) to secrete elevated levels of MCP1, IL-6, IL-1β, TNF-α, and leptin, while repressing adiponectin levels [124, 125]. Adiponectin is an important adipokine that is secreted by adipocytes and is known to play a significant role in obesity-induced insulin resistance. Numerous animal studies have shown that increased adiponectin levels are inversely proportional to the concentration of ceramides, an important factor in the modulation of obesity-induced insulin resistance [126, 127]. Additional evidence shows that adiponectin levels are negatively correlated with increased TNF-α levels [121, 124, 126]. Likewise, growing evidence suggests that decreased adiponectin levels with concomitant increased TNF-α levels not only perpetuate obesity-induced insulin resistance, but are key cytokines that aggravate the metabolic syndrome [127, 128]. Increased adiponectin levels are associated with diminished systematic inflammation and lipid accumulation, leading to reduced vascular dysfunction that is linked to the metabolic syndrome.
green rooibos extract and pure aspalathin are able to modulate glucose metabolism by inhibiting α-glucosidase enzyme activity and promoting glucose uptake in pancreatic and skeletal muscle cells as well as improving glucose tolerance in streptozotocin-induced diabetic Wistar rats. Mikami et al. [141] demonstrated that green rooibos extract and aspalathin were effective at reducing blood glucose levels of nondiabetic mice following ingestion of glucose, sucrose, and starch solutions, while suppressing the activities of α-glucosidase and α-amylase, key enzymes involved in carbohydrate hydrolysis. Mazibuko et al. [92, 142] further investigated the molecular mechanisms associated with the ameliorative effect of pure aspalathin and an aspalathin-rich green rooibos extract on palmitate-induced insulin resistance in C2C12 myotubes and 3T3-L1 adipocytes. Both the extract and compound were able to reverse palmitate-induced insulin resistance by increasing levels of GLUT4 through the suppression of PKC and NF-κB, while activating AMPK. Son et al. [143] supported these findings showing that aspalathin treatment improved glucose tolerance in obese (ob/ob) mice, while similarly enhancing glucose uptake by promoting AMPK phosphorylation and GLUT4 translocation in L6 myotubes. Smit et al. [144] showed that aspalathin promotes insulin sensitivity in cardiomyocytes from young and aged rats, but not in high-caloric diet animals, through a PI3K-dependent mechanism. Aspalathin can protect cardiomyocytes from doxorubicin-induced cardiotoxicity by increasing autophagy, while simultaneously decreasing apoptosis [102, 145].

Furthermore, both in vitro and in vivo studies have indicated that aspalathin can reduce hyperlipidaemia [91, 146]. The effect of aspalathin to diminish cholesterol, triglycerides, and VLDL- and LDL cholesterol levels, while increasing high-density lipoprotein cholesterol levels, has been investigated in a few studies. Najafian et al. [146] showed that streptozotocin-induced diabetic male Wistar rats receiving 5, 10, and 40 mg/kg of aspalathin for 21 days displayed a dose-dependent decrease in lipid levels in conjunction with reduced blood glucose concentrations. Similarly, in a study by Johnson et al. [91], a 6-week treatment with aspalathin modulated lipoprotein clearance in a dose-dependent manner in db/db mice, with a higher dose (130 mg/kg) of the compound being more effective than a lower dose (13 mg/kg). Additional evidence by Van der Merwe et al. [147] demonstrated that an aspalathin-rich green rooibos extract significantly reduced serum total cholesterol of male Fischer rats after 90 days of treatment. Collectively, these results indicate that aspalathin may beneficially modulate glucose and lipid metabolism, thereby ameliorating the complications associated with metabolic syndrome.

The proposed cellular mechanisms by which aspalathin improves glucose and lipid metabolism

The cellular mechanism by which aspalathin targets metabolic syndrome and improves glucose and lipid clearance remains to be fully elucidated. However, it has been proposed that by suppressing fatty acid synthesis, aspalathin enhances CPT1 expression and subsequently increases β-oxidation in muscle tissue [92]. The latter process is under the control of essential lipid metabolism genes, including ACC, FAS, and SCD1, that play an integral role in the development of insulin resistance in fat, liver, muscle, and heart tissue. Furthermore, PPARγ, SREBP-1/2, and
ChREBP are transcriptional factors that regulate and control the expression of these enzymes involved in the lipogenic process [148]. However, this process can be repressed through AMPK phosphorylation [149]. Aspalathin activates AMPK and reduces the expression of hepatic enzymes and transcriptional regulators that are associated with either gluconeogenesis and/or lipogenesis [91, 92, 102, 139, 143, 144, 150]. These studies proved that aspalathin controlled the balance between anabolism and catabolism [91,92, 102,139,143,144,150]. These studies proved that aspalathin controlled the balance between anabolism and catabolism [91,92, 102,139,143,144,150].

Table 6  Summary of studies related to the antioxidant, antidiyslipidaemic, antidiabetic, and anti-inflammatory activities of aspalathin (ASP) and aspalathin-rich green rooibos extracts.

<table>
<thead>
<tr>
<th>Experimental model</th>
<th>Treatment and dose</th>
<th>Experimental outcome</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>L6 Myoblasts, RIN-SF cells and type 2 diabetic (db/db) mice</td>
<td>ASP: Cell culture dose (1–100 µM) ASP: Dietary dose in mice (0.1–0.2%)</td>
<td>Improved glucose uptake, insulin secretion, and glucose tolerance.</td>
<td>[139]</td>
</tr>
<tr>
<td>Online HPLC-biochemical assay for α-glucosidase inhibitory activity, C2C12 myotubes, Chang (CCL-13) cells, and streptozotocin-induced diabetic rats</td>
<td>ASP: Cell culture dose (1, 10, and 100 µM) Extract: Cell culture dose (5 × 10−5–5 µg/mL) Extract: In vivo dose (3, 25, 30, or 300 mg/kg BW)</td>
<td>Displayed α-glucosidase inhibitory activity, improved glucose tolerance, and dyslipidemia.</td>
<td>[140,146]</td>
</tr>
<tr>
<td>Nondiabetic ddY mice; in vitro α-glucosidase and α-amylase inhibitory assays</td>
<td>ASP: In vitro dose (0, 0.5, 1, 2, 4, 8 mg/mL) ASP: In vitro dose (20 mg/mL/100 g BW) Extract: In vitro dose (0, 2, 5, 10, 20, 40 mg/mL) Extract: In vivo dose (80 mg/mL/100 g BW)</td>
<td>Reduced blood glucose levels following ingestion of glucose, sucrose, and starch solutions. Also inhibited the activities of α-glucosidase and α-amylase.</td>
<td>[141]</td>
</tr>
<tr>
<td>L6 Myotubes, RIN-SF cells and obese (db/db) mice</td>
<td>ASP: Cell culture dose (0–100 µM) ASP: Dose in mice (100 mg/kg/day/mouse)</td>
<td>Dose-dependently increased glucose uptake, enhanced GLUT4 translocation to plasma membrane, and promoted AMPK phosphorylation in L6 myotubes. Reduced oxidative stress in RIN-SF cells and improved fasting plasma glucose levels in mice.</td>
<td>[143]</td>
</tr>
<tr>
<td>Caenorhabditis elegans</td>
<td>ASP: In vitro dose (0, 10, 20, 50 µM)</td>
<td>Promoted longevity by targeting stress and ageing-related genes, reducing the endogenous intracellular level of reactive oxygen species.</td>
<td>[152]</td>
</tr>
<tr>
<td>HUVECs, human blood samples, and C57BL/6 mice (ex vivo model)</td>
<td>ASP: Cell culture dose (1–50 µM) ASP: Ex vivo dose (4.5, 9.1, 18.1, 27.1, and 45.2 µg/mouse)</td>
<td>Demonstrated antithrombotic activities by prolonging activated partial thromboplastin time and blocking platelet aggregation and activities of thrombin and activated factor X.</td>
<td>[156]</td>
</tr>
<tr>
<td>HUVECs and mice</td>
<td>ASP: Cell culture dose (1–50 µM) ASP: In vitro dose (4.5, 9.1, 27.1, or 45.2 µg/mouse)</td>
<td>Prevented high-glucose-mediated vascular hyperpermeability, adhesion of monocytes, and expression of cell adhesion molecules. Inhibited generation of ROS and activation of NF-κB or ERKs.</td>
<td>[157,162,163]</td>
</tr>
<tr>
<td>HUVECs</td>
<td>ASP: Cell culture dose (1–50 µM)</td>
<td>Ameliorated HMGB1-induced septic responses.</td>
<td>[159]</td>
</tr>
<tr>
<td>3T3-L1 Adipocytes</td>
<td>ASP: Cell culture dose (10 µM) Extract: Cell culture dose (10 µg/mL)</td>
<td>Reversed palmitate-induced insulin resistance by repressing NF-κB, IRS1 and AMPK phosphorylation, and increased AKT activation; only the extract upregulated GLUT4 protein expression.</td>
<td>[92]</td>
</tr>
<tr>
<td>In vitro xanthine oxidase inhibitory activity assay and mice</td>
<td>ASP and extract: Effective dose used (4.5 µg/mL)</td>
<td>Competitively inhibited xanthine oxidase. In hyperuricaemic mice, markedly suppressed increased plasma uric acid levels in a dose-dependent manner.</td>
<td>[153]</td>
</tr>
<tr>
<td>H9c2 cells, db/db mice and cardiomyocytes from rats</td>
<td>ASP: Cell culture dose (1 and 1000 µM) ASP: In vivo dose (13 and 130 mg/kg BW/day)</td>
<td>Improved diabetes associated cardiac deregulations, including enhanced glucose uptake, reversed impaired myocardial substrate metabolism, inhibited inflammation, lipid storage, oxidative stress, and cardiac remodelling. Reversed doxorubicin-induced cardiotoxicity by activating AMPK and reducing tumour protein p53 expression.</td>
<td>[88,91,102,144,145]</td>
</tr>
<tr>
<td>Rats</td>
<td>Extract: In vivo dose of 29.5 mg/kg BW/day</td>
<td>Lowered serum total cholesterol and iron levels, whilst increasing alkaline phosphatase enzyme activity and liver GSH levels.</td>
<td>[147,151]</td>
</tr>
<tr>
<td>Diabetic nonhuman primates</td>
<td>Extract: In vivo dose (90 mg/kg BW)</td>
<td>Improved glucose tolerance, reduced total cholesterol, and LDL levels. Increased plasma coenzyme Q10 and decreased oxidative status.</td>
<td>[154]</td>
</tr>
</tbody>
</table>
As opposed to glucose oxidation, has been linked to reduced car-
the diabetic heart, an abnormal increase in fatty acid oxidation,
in fatty acid synthesis and subsequent
β-oxidation [102]. AMPK is a major energy regulator that
creased FFA uptake and oxidation through the reduced phospho-
cose and lipid metabolism, specifically by reducing abnormally in-
dative damage was associated with its modulatory effect on glu-
culate glucose concentration, the capacity of aspalathin to prevent oxi-
 to reduce oxidative stress could be attributed to its inhibitory ef-
effect on xanthine oxidase, a known superoxide radical-producing
zyme [153]. Recently, Orlando et al. [154] showed that an aspa-
lathin-rich green rooibos extract (12.8% aspalathin content) ad-
istered at 90 mg/kg three times daily with meals to high-fat
fed diabetic vervet monkeys protected against LDL oxidation and
preserved endogenous coenzyme Q10 levels. This supports out-
comes of the study by Marnewick et al. [155], showing that the
consumption of six cups of rooibos tea improved plasma lipid
and oxidative stress levels in adults at risk for developing cardio-
vascular disease.

Recent studies from our laboratory have also reported on the
potential of aspalathin to protect cardiac cells against oxidative
stress-associated damage (Table 6). In cardiomyocytes isolated
from diabetic rats, a fermented rooibos extract (0.36% aspalathin)
prevented ROS-induced apoptosis by increasing intracellular GSH
levels [161]. Furthermore, in cardiomyocytes exposed to a high
-glucose concentration, the capacity of aspalathin to prevent oxy-
dative damage was associated with its modulatory effect on glu-
cose and lipid metabolism, specifically by reducing abnormally in-
creased FFA uptake and oxidation through the reduced phosho-
rylation of AMPK [102]. AMPK is a major energy regulator that
plays a role in the reversal of peripheral insulin resistance through
the modulation of β-oxidation [92, 142, 143]. This kinase increases
β-oxidation and improves peripheral insulin sensitivity through
phosphorylation and inactivation of ACC, a rate-limiting enzyme
in fatty acid synthesis and subsequent β-oxidation. However, in
the diabetic heart, an abnormal increase in fatty acid oxidation,
as opposed to glucose oxidation, has been linked to reduced car-
diac efficiency. In a recent study [102], we showed that in the dia-
abetic heart, aspalathin modulates AMPK hyperactivation and im-
proves glucose oxidation. This favourable shift in cardiac energy
substrate, in favour of glucose oxidation, is believed to be impor-
tant to protect a diabetic heart at risk of developing heart failure.
The ameliorative effects of aspalathin were confirmed in the
hearts of db/db mice and cardiomyocytes exposed to high glucose
concentrations [88], showing that an increased expression of
Nrf2, an essential transcriptional factor that is upregulated in re-
ponse to oxidative stress and other stresses associated with the
metabolic syndrome [89], plays a partial role in the protective ef-
efect of aspalathin. This study further showed that the upregulated
expression of Nrf2 enhanced the endogenous antioxidant systems
such as GSH and superoxide dismutase, as well as UCP2, resulting
in improved cardiac ultrastructure. Although these findings need
to be confirmed in other models, the results infer that aspalathin
might be a useful therapeutic against endogenous oxidative stress
and protect cardiovascular cells from diabetes-associated complica-

In addition to the ability of aspalathin to reduce oxidative
stress, anti-inflammatory properties have also been demonstrated
for this dihydrochalcone. Lipopolysaccharide is a known means
of inducing vascular inflammation, both in vitro and in vivo mod-
els. Aspalathin treatment suppressed lipopolysaccharide-induced
membrane permeability and CAM in both human endothelial cells
and in mice [162]. Furthermore, aspalathin ablated this effect by
downregulating the expression of TNF-α, IL-6, and NF-κB. In a fol-
low-up study, the authors demonstrated that 10–30 μM of aspa-
lathin averted HMGB1-mediated vascular inflammation and hyper-
permeability by inhibiting the expression of CAM in both an in vi-
tro (HUVECs) and in vivo (C57BL/6 mouse) model [158]. Although
additional evidence is required to confirm these findings, a study
by Ku et al. [157] showed aspalathin suppressed ROS as well as ac-
tivated NF-κB and monocyte adhesion in both an in vitro cell and in
 vivo mouse model. Elevated plasma levels of sEPCR have been
found to increase vascular inflammation and subsequent throm-
botic risk [159]. Kwak et al. [163] showed that aspalathin treat-
ment inhibited phorbol 12-myristate 13-acetate-induced TNF-α,
IL-1β, and CLP-induced EPCR shedding by inhibiting the phospho-
rylation of several kinases known to increase thrombin gener-
ation. These results present strong evidence in support of aspala-
thin as a nutraceutical to protect against metabolic syndrome
and associated complications such as glucose and lipid intoler-
ance, as well as oxidative stress and inflammation that may result
in accelerated cell injury. The ameliorative properties of aspalathin
against glucose and lipid metabolic perturbations in various tissue
targets are summarised in Fig. 7.

Herb-drug interactions
The increasing custom of the health conscious public to supple-
ment their diets with natural products to enhance health and
well-being is of concern due to possible herb-drug interactions in
the growing population of patients on chronic medications [164].
Natural products are generally considered to be safe with little re-
gard for potential adverse effects. Patients are drawn to using
these products as adjunctive supplements to enhance the thera-
petic efficacy of their medication, mostly without informing
their health practitioner. In most countries, natural products are sold over-the-counter or are freely available in supermarkets with sparse information about their health risk benefits, either as a monotherapy or in combination with other chronic medications. It is reasonable to assume that the concurrent use of aspalathin-based nutraceuticals with chronic blood glucose-lowering medication by type 2 diabetic patients will escalate. Although anecdotal evidence suggests that consumption of rooibos is generally regarded as safe, recently, two case studies have suggested the potential for herb-drug hepatotoxicity. In the first case [165], a 42-year-old woman treated for a low-grade B-cell malignancy with rituximab and maintained on prednisolone and co-trimoxazole daily, presented with elevated liver enzymes. She was advised to stop drinking rooibos flavoured with small amounts of strawberry, chamomile, and petals of daisy and discontinue her prophylactic antibiotic (co-trimoxazole). One week later, her liver enzymes returned to normal and she resumed her prophylactic co-trimoxazole treatment without further adverse effects. A second case...
study [166, 167] involved a 52-year-old hyperlipidaemic patient on atorvastatin who developed clinical symptoms of hepatotoxicity following increased consumption of a rooibos-buchu herbal tea. In the latter case, the presence of buchu, an indigenous South African medicinal plant shown to inhibit CYP3A4 [160], a major phase I metabolising enzyme of atorvastatin, confounded results. Although these two case studies do not conclusively infer causality, the sparsity of information relating to the potential of rooibos- and aspalathin-drug interactions prompted us to investigate their potential interaction with chronic medications such as statins or oral hypoglycaemic drugs. Using an in vitro recombinant CYP450 enzyme assay, both an aspalathin-rich green rooibos extract and aspalathin dose- and time-dependently inhibited CYP3A4, cautioning against the potential of a herb-drug interaction with hypoglycaemic drugs such as sulfonyleureas and statins, including atorvastatin [168]. However, these findings still need to be confirmed by in vivo pharmacokinetic and pharmacodynamic studies.

Conclusions

The increase in metabolic syndrome, partially due to a sedentary lifestyle and poor diet, and consumers looking for “quick fix answers” create increasing opportunities for the development of natural products to manage clinical risks such as increased blood sugar and cholesterol. Such products need scientific scrutiny to understand the mechanisms of action and ensure safety with minimum adverse reactions. Research to date on aspalathin and aspalathin-rich green rooibos extracts has laid the foundation for their use as adjunctive therapeutics. Issues that need to be addressed are effective dose, safety, potential herb-drug interactions, and improved bioavailability of aspalathin.

Conflict of Interest

The authors declare no conflict of interest.

References


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