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Rooibos phenolic constituents as a dietary supplement for physical performance: Evidence to date

Oiva Viety Kamati[a], Simeon Davies[a,b], Roan Louw[c], Laura Bragagna[d], Karl-Heinz Wagner[d], Jeanine L Marnewick[a,*]

[a] Applied Microbial and Health Biotechnology Institute, Cape Peninsula University of Technology, Cape Town, South Africa
[b] Faculty of Business and Management Sciences, Cape Peninsula University of Technology, Cape Town, South Africa
[c] Human Metabolomics, North West University, Potchefstroom, South Africa
[d] Department of Nutrition Sciences, Faculty of Life Sciences, University of Vienna, Austria

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ABSTRACT

Consumers all over the world incorporate natural phytochemicals into their diets on a regular basis in order to maintain and improve health and prevent diseases. Athletes and sports professionals are increasingly turning to naturally occurring plant extracts and phytochemicals to boost physical performance, aid in workout recovery, and maintain health. Even though exercise has numerous scientifically proven health benefits, it can also be compared to a double-edged sword in which low levels of reactive oxygen species (ROS) formation and generation induce beneficial physiological adaptation in working skeletal muscles, whereas high levels of ROS may harm critical cellular structures. However, Rooibos, a native South African herbal tea with unique polyphenolic components and bioactivities, has the ability to increase the endogenous antioxidant defense system and neutralize ROS. A growing body of evidence suggests that Rooibos may be useful as an ergogenic aid, offering athletes and the greater fitness community an efficacious product. Previously, Rooibos has been linked to anti-inflammatory, anti-cancer, antimicrobial, cardioprotective, and other health benefits. In this narrative review, we primarily focus on published human intervention studies that evaluated Rooibos' ergogenic aid potential, its modulatory effect on healthy persons' antioxidant defense systems and improved exercise outcomes.
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1. Introduction

Despite the undeniable health benefits of exercise, under certain conditions, such as acute exhausting and strenuous exercise, an increased formation and generation of reactive oxygen and nitrogen species (RONS) may occur because of higher oxygen consumption and utilisation, often leading to oxidative stress and resultant damage to critical cellular macromolecules including DNA, lipid and protein (Luna and Estévez, 2018). Damage to these components may result in cellular dysfunction, impairment and potential development of several diseases. In addition, excessive RONS generated during strenuous or exhausting exercise activities may overwhelm the muscles' antioxidant buffering capacity and eventually cause force production inhibition, muscle damage, fatigue, pain, inflammatory responses and overall poor exercise performance and recovery (Steinbacher and Eckl, 2015; Bessa et al., 2016; D'Angelo and Rosa, 2020). Although living organisms naturally possess an endogenous antioxidant defence system that counteract against RONS, through its antioxidant substances that work synergistically to delay, detoxify, attenuate oxidative stress-induced damage and maintain cellular homeostasis (Elejalde et al., 2021). This endogenous antioxidant system is not always 100 % effective or sufficient to suppress challenges posed by RONS excessive productions.

The endogenous antioxidant defence system comprises of enzymatic antioxidant compounds [superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), glutathione reductase (GR) and glutathione-S-transferase (GST)] (Elejalde et al., 2021; Demirci-Çekiç et al., 2022) and non-enzymatic antioxidant compounds such as glutathione that function as preventive, interceptor, or scavenger of

Abbreviations: CAT, Catalase; CCl4, Carbon tetrachloride; CDs, Conjugated dienes; CVD, Cardiovascular diseases; DEP, Diesel exhaust particles; DNA, Deoxyribonucleic acid; GPx, Glutathione peroxidase; GR, Glutathione reductase; GSH, Reduced glutathione; GSSG, Oxidised glutathione; GST, Glutathione-S-transferase; LPO, Lipid peroxidation; MDA, Malondi aldehyde; Nrf-2, Nuclear factor erythroid-related factor-2; RONS, Reactive oxygen and nitrogen species; ROS, Reactive oxygen species; SOD, Superoxide dismutase; USA, United State of America; USDA, United States Department of Agriculture

* Corresponding author at: Applied Microbial and Health Biotechnology Institute, Cape Peninsula University of, Technology, PO Box 1906, Bellville, 7535, Cape Town, South Africa.
E-mail address: marnewickj@cput.ac.za (J.L. Marnewick).

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RONS (Kawamura and Muraoka, 2018). Non-enzymatic antioxidant compounds exist in two sub-groups, metabolic non-enzymatic antioxidants and nutrient non-enzymatic antioxidants compounds acquired through dietary intake, and they exhibit unique antioxidant properties, which maximise their effectiveness (Mirończuk-Chodakowska, Witkowska and Zujko, 2018). Thus, intake of plant bioactive components, such as polyphenols with known antioxidant and other bioactivities properties are proving to be potential game changers in effectively mitigating the deleterious effects caused by RONS production, such as found during strenuous exercise regimes. Because of its polyphenolic, flavonoid-rich content, Rooibos has shown the ability to boost the antioxidant defence system mechanisms both *in vitro* and *in vivo*. Rooibos herbal tea has a divergent profile of polyphenolic compounds and is the rare dietary source of the dihydrochalcones,-aspalathin and nothofagin, which are potent antioxidants (Timoth and Emma, 2020). Awoniyi and co-workers investigated the protective effects of Rooibos against induced oxidative stress damage, and they reported that its consumption significantly increased the SOD activity and GSH level in experimental rats with subsequent protection of the testicular tissues against induced oxidative lipid damage (Awoniyi et al., 2011). Rooibos also efficiently protected against induced oxidative stress damage by regulating glutathione metabolism (GSH and GSH/GSSG ratio) and modulating SOD and CAT activities, subsequently enhancing the rat's antioxidant defence system (Hong, Lee and Kim, 2014). A study investigating hyperglycemia-induced oxidative damage on the heart reported aspalathin, the unique Rooibos polyphenolic compound, to effectively maintain cellular homeostasis, protect the myocardium-and activate nuclear factor erythroid-related factor-2 (Nrf-2), a transcription factor that regulates redox homeostasis. This action subsequently caused the increased expression of antioxidant enzyme genes resulting in elevated antioxidant capacity and efficient neutralisation of generated RONS by the endogenous antioxidants compounds (Dludla et al., 2017). Ajuwon et al. (2014) also concluded that in an acute lipopolysaccharide-induced liver injury experimental study, prior treatment with Rooibos modulated the rats' endogenous antioxidant capacity, reversed the hepatic antioxidant enzymes (SOD, CAT, GPx and GR) activities and restored the GSH and GSH/GSSG ratio to baseline values. In one of the very few human intervention studies done using Rooibos, Marnewick and co-workers reported a significantly improved redox status of glutathione as well as a significant decrease in oxidative damage to lipids when fermented Rooibos was consumed for 6 weeks by adults at risk for developing cardiovascular diseases (CVD) (Marnewick et al., 2011). The modulation of the antioxidant enzyme activities/potential and blood redox status in these studies has been ascribed to the ability of Rooibos to cause an upregulation of the cellular synthesis of GSH molecules and its polyphenolic-rich antioxidant components that can chelate metals, scavenge free radicals, trap RONS (*e.g.*, superoxide, hydroxyl, hydrogen peroxide), break chains of radical sequences and quench singlet oxygen (McKay and Blumberg, 2007; Smith and Swart, 2016; Dludla et al., 2020).

In the sports/fitness arena, various strategies including the use of ergogenic aids are employed by athletes and fitness individuals to enhance performance, recovery and to mitigate muscle pain and fatigue onsets. Thein and co-workers defined an ergogenic aid in the context of sports as "a technique or substance used to enhance performance" (Thein and Landry, 1995), and as such, can be dietary, pharmacologic, physiological, or psychological, with a variety of forms. The available research indicates that nutritional supplements for athletes can encourage muscle growth, improve athletic performance, and speed up post-workout recuperation (Bonilla et al., 2023). Caffeine, beta-alanine, and creatine are among those dietary sports supplements that have received much attention from the scientific community over the past few years as ergogenic aids.

Davies and colleagues brought attention to Rooibos and its phenolic compounds to serve as an ergogenic aid that could be useful for the sports and fitness community (Davies et al., 2023). This review aims to explore and summarize current literature regarding Rooibos' potential to alleviate exercise-induced oxidative stress and enhance exercise performance in humans. Relevant bioactivities, consumption and bioavailability are also discussed.

2. Rooibos, as a polyphenolic-rich source, its uniqueness, and bioavailability

Rooibos (*Aspalathus linearis (Burn. F) R. Dahlgren, Fabaceae*) is a South African indigenous shrub native to the Cederberg Mountains and neighbouring areas in the Western Cape Province. It is characterised by a strong two-metre-long taproot, reddish-brown branches and bright green, needle-shaped leaves (Johnson et al., 2018). Rooibos herbal tea is prepared from the processed leaves and stems of the *Aspalathus linearis* plant. Currently, two types of Rooibos herbal teas (fermented/traditional and unfermented/green) are produced depending on the processing method. Fermented Rooibos, also known as red or traditional Rooibos, is made by cutting the stems and leaves into fine pieces, wetting them, and piling them in heaps exposed to the African sun for 12-24 h to stimulate chemical oxidation, which results in the characteristic aroma and red colour. Unfermented Rooibos, also known as green Rooibos, is created by immediately oven-drying the new harvest to avoid oxidation before cutting it into pieces (McKay and Blumberg, 2007). During the oxidation processes/fermentation, a loss of some of the main phenolic components, such as aspalathin and nothofagin, occurs, which impacts the overall antioxidant capacity (Swart and Smith, 2016; Johnson et al., 2018). In general, Rooibos contains an abundance of phenolic compounds with various bioactive properties (Marnewick et al., 2009; Joubert and de Beer, 2011; Canda et al., 2014; Davies et al., 2019a) including the unique dihydrochalcone, aspalathin, and cyclic dihydrochalcone, aspalalinin (Shimamura et al., 2006), which only found in Rooibos (Fig. 1). Aspalathin and nothofagin are the main flavonoids in Rooibos, although aspalathin tends to be lower in the fermented/traditional when compared to the unfermented/green type, due to the chemical oxidation/fermentation process.

Research on the health impact, including the safety of Rooibos, has steadily been growing in the past three decades (Marnewick et al., 2000; Kreuz et al., 2008, 2011; Chen et al., 2013; Abdul and Marnewick, 2021). Despite progress, there is still much to be done in terms of improving its bioavailability. When Rooibos is consumed, the polyphenolic compounds are absorbed in the gut and undergo hydrolysation and conjugation to form free and absorbable metabolites (aglycones). A study by Kreuz et al. (2008) in pigs, where 157 to 167 mg of aspalathin /kg/d was administered orally for 11 days, reported that only methylated aspalathin metabolites were found in the urine, and nothing could be detected in the plasma. Only 0.1 % to 0.9 % of administered aspalathin was found on day 7 and 11. The absence of detectable metabolites in plasma and relatively small, detected amounts in urine, led to the assumption that extensive metabolism of aspalathin occurred. Stalmach et al. (2009) reported the detection of O-linked methyl sulphate, glucuronide metabolites, O-methyl-aspalathin-O-glucuronide and eriodictyol-O-sulphate in human urine after an acute dose intake of 500 mL fermented and/or unfermented Rooibos beverage. O-methyl-aspalathin-O-glucuronide and eriodictyol-O-sulphate (229 nmol and 68 nmol, respectively) were the most excreted metabolites 24 h post consumption of the unfermented and fermented Rooibos beverage. Furthermore, aspalathin metabolites were excreted within 5 h post-consumption, while eriodictyol-O-sulphate excretion occurred 5–12 h post-consumption, indicative of absorption in the small and large intestines. Additionally, no flavonoid metabolites were detected in the plasma of the study participants, with the excreted metabolites only accounting for

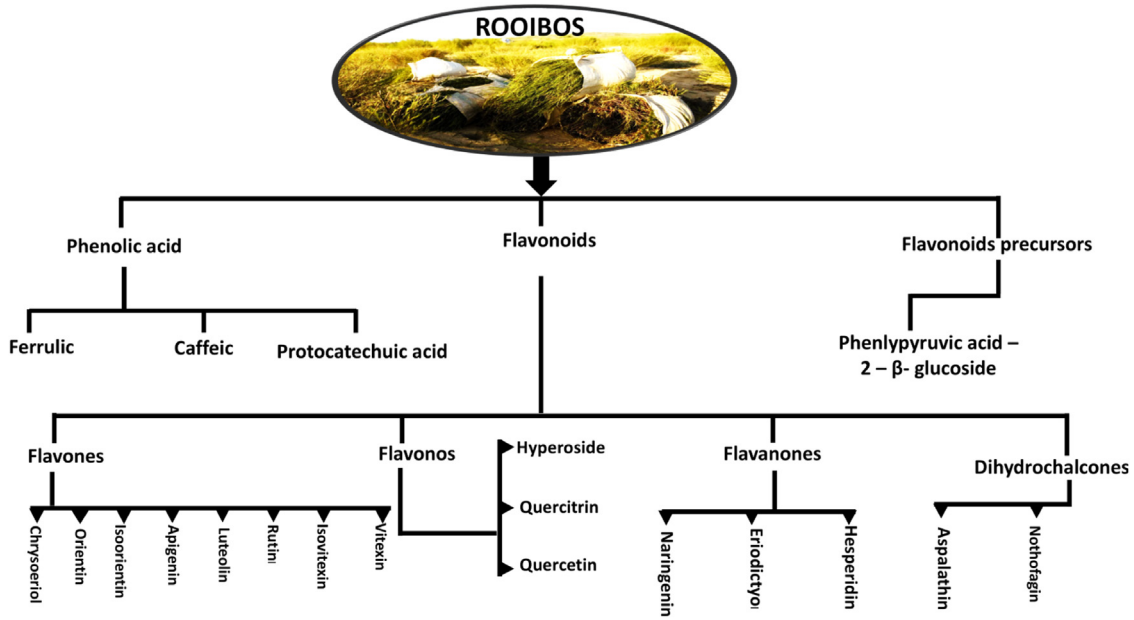


Fig. 1. Classification of common polyphenolic constituents present in Rooibos.

0.09 % and 0.22 % of the consumed fermented and unfermented Rooibos flavonoid content. Breiter et al. (2011) also confirmed the findings of Rooibos metabolites in participants with methylated aspalathin metabolites as the primary metabolite excreted in the urine. In a review by Afrifa et al. (2023) reported that only about 0.76 nmol of the quantified Rooibos flavonoids were bioavailable during their maximum concentration in plasma, accounting for only 0.26 % of the 758 μmol total amount ingested. Current literature predominantly suggests poor bioavailability of Rooibos constituents. Therefore, strategies or modalities of bioavailability enhancers such as molecular enhancers or adjuvants, nanoparticles or nanocarriers, encapsulation systems, conjugation approaches of developing derivatives and/or analogs of polyphenols may be utilised to protect Rooibos bioactive compounds from oxidation and degradation, improve absorption, solubility, stability and penetration of which eventually enhance Rooibos bioactive compounds or metabolites (Yin et al., 2022; Sahraeian, and Golmakani, 2024)

3. Daily consumption of polyphenolics and Rooibos

As mentioned before, there is a growing interest in polyphenolic compounds when considering their antioxidant properties in sports and recreation. However, to date, there has yet to be a recommended daily intake determined for these compounds. Various studies have previously reported on the daily dietary intake of total phenolics, flavonoids and other phenolic compounds in different populations worldwide. A review by Del Bo et al. (2019), reported a daily intake of 890 mg to 910 mg of total polyphenols, 360 to 380 mg of total flavonoids and 410 to 450 mg of total phenolic acids. Using the United States Department of Agriculture (USDA) and Phenol Explorer databases Del Bo et al. (2019), further reported on differences in polyphenolic intakes when considering different geographical areas, with examples including Japan, with an estimated average polyphenolic intake of 1500 mg/day, while European countries at 900 mg/day and North and South America indicating 800 mg/day. For South Africa, very few studies exist reporting on the daily intake of polyphenolic compounds. A study by Louwrens et al. (2009) using secondary data from the Department of Health (1983 – 2000), reported on the adult average daily intake of fruits and vegetables, and although it has increased, many South Africans do not consume the recommended daily intake of 5–7 servings (400 g). A study conducted in 2011 in a South African adult population at risk for developing cardiovascular disease measured the daily flavonoid intake using daily dietary records completed by the participants and reported an average of 343 mg per day (Marnewick et al., 2011). This is comparable with the study by Huang et al. (2020) that reported an average daily flavonoid intake of 379.1 mg by 9773 adults from the United States of America (USA), using 24 h dietary recall methodology.

When considering the daily intake of polyphenolic compounds by athletes, few studies worldwide have reported on this. One study included college athletes at the Dakota State University in the USA. It showed an average intake of 73.12 mg of flavonoids daily, which is lower than the typical American population (Chen, 2014). In contrast, numerous studies and review articles can be found investigating the daily intake of a specific polyphenol-rich extract by athletes to measure any possible improvement in exercise outputs, such as the study by Overdevest et al. (2018) who reported trained athletes consuming 500 mg daily of a customised citrus flavonoid extract for 4 weeks demonstrated a significantly increased power output and a considerably decreased oxygen consumption/power ratio during the exercise test. A systematic review and meta-analysis by Somerville et al. (2017) on polyphenols and performance concluded that polyphenol supplementation for at least 7 days benefits exercise performance in healthy people but concluded also that an optimal dose still needs to be established. A recent review by Bojarczuk and Dzitkowska-Zabielska (2022) on this topic is more conservative in their conclusion, stating that data is still insufficient to suggest that antioxidant polyphenols can benefit athletes and that more studies are needed.

In the absence of having a recommended daily intake, Piek and co-workers reported on how to prepare the “optimal cup of Rooibos” in the context of achieving the highest total polyphenol content and total antioxidant capacity (Piek et al., 2019). Their results showed to achieve the “optimal cup”, the Rooibos plant material will need to be steeped for 10 min or longer, and preferably in a tea pot and not a mug/cup. They concluded that of the consumers they interviewed, only 15.9 % consumed the “optimal cup” based on the steeping time they reported. They also established that only 31.5 % of the respondents consumed Rooibos on a weekly basis. Considering that a previous report (Marnewick et al., 2011) suggested a consumption of six cups of Rooibos daily to benefit from its health properties, the intake reported by Piek and co-workers is considerably less.

4. Rooibos and oxidative lipid damage

Lipids are the building blocks responsible for the structure of cells and are involved in energy storage, cell membrane structural components, cell metabolism, signal transduction and other normal cellular functions (Birben et al., 2012). Cells are vulnerable to oxidative damage when under stress, particularly due to the composition of their fatty acids. These fatty acids consist of a chain of methyl groups with a carboxyl group located at one end. Lipid peroxidation (LPO) often occurs when RONS remove a hydrogen atom from a methylene group next to a carbon double bond to form a carbon-centred radical, which further reacts with oxygen molecules in the cell membrane to form the peroxyl radical that subsequently exacerbates the chain reactions and cause more damage to the lipid structure (Birben et al., 2012). The deterioration of these lipid structures results in the disturbance of cell membrane integrity, loss of membrane fluidity, inactivation of membrane-bound enzyme receptors and, subsequently development of various cellular dysfunctions and impairments (Kurutas, 2015). Several *in vitro* and *in vivo* studies have shown Rooibos to prevent or reduce oxidative damage to lipids (Marnewick et al., 2011; Smith and Swart, 2016; Dludla et al., 2017; Lawal et al., 2019; Akinfenwa et al., 2021). Kucharská et al. (2004) reported that prior consumption of Rooibos diminished carbon tetrachloride (CCl4) – induced hepatic steatosis and cirrhosis in rats by enhancing the antioxidant capacity of the liver resulting in a significant decrease of hepatic malondialdehyde content – a standard indicator of lipid oxidation. The study by Marnewick et al. (2011) reported that the intake of six cups of fermented Rooibos herbal tea daily resulted in an improved plasma total polyphenolic content, lipid profile and glutathione redox status of the adult study population at risk of developing cardiovascular diseases. Additionally, a significant decrease in the oxidative lipid damage markers, conjugated dienes (CDs) and MDA was shown in this study. Lawal et al. (2019) also reported a similar finding in a study that investigated the cardioprotective effects of Rooibos against diesel exhaust particles (DEP) - induced inflammation and oxidative stress in rats exposed to 0.7mg/kg twice a week for two weeks. In that study, Rooibos intake was 50 mg/kg for 4 weeks, which significantly attenuated MDA and CD levels in rats' hearts and aorta, which was indicative of the protective effects of Rooibos against induced oxidative damage. Results from these studies also suggested Rooibos phenolic components were also involved with scavenging, chelating and binding of RONS, stabilising them into less active radicals and subsequently reducing or breaking the LPO cascade.

5. Rooibos polyphenolics as an emerging ergogenic aid

As mentioned, the relationship between exercise and oxidative stress is complex, but it often depends on the mode, type, duration, and intensity of the exercise (Ammar et al., 2020). In general, physical activity or exercise increases oxygen consumption since it causes a greater/increased energy demand, which causes skeletal muscles to produce more RONS. These reactive species are mainly produced aerobically during cellular respiration via the incomplete oxygen reduction in the mitochondrial electron transport chain (Wang and Hai, 2016). Jackson et al. (2016) indicated that prolonged or intense muscle contractions alter the physiological environment in the muscle fibre and predispose them to a higher rate of RONS generation. In 2004, Arbogast and Reid showed that muscle contraction is associated with an increased muscle temperature, increased carbon dioxide tension, and decreased cellular pH that can stimulate and accelerate RONS production within the muscles (Arbogast and Reid, 2004). This same idea was reported by Ferreira and Reid (2008), who found that increased oxygen consumption in muscle fibre during exercise reduced oxygen intracellular tension, which enhanced RONS production. To minimise the effects of oxidative stress induced during strenuous exercise or physical activity, many athletes and sports professionals have resorted to using antioxidant-rich supplements. These dietary supplements are mainly based on the understanding that they are natural, safer, and more affordable and may act as an ergogenic aid to improve or enhance exercise performance and recovery.

Only a few research studies have reported on using Rooibos in some exercise investigation, whether in experimental animals or with human participants. When considering the experimental animal studies, Watanabe and coworkers (2014) investigated the effects of Rooibos on physical endurance in eighteen three-week-old male Balb/c mice. They reported that consumption of green/unfermented Rooibos or aspalathin (the unique Rooibos dihydrochalcone) for 5 weeks prolonged the swimming time of the experimental mice, although not significantly. Interestingly, a significant increase in hepatic and skeletal muscles' glycogen levels was shown for the Rooibos and aspalathin consuming groups. The authors concluded that increased skeletal muscle glycogen levels can explain the observed improved swimming performance because glycogen acts as an energy source, allowing the Rooibos- and aspalathin-fed mice to go for significantly more extended periods. In another experimental animal study, the authors reported on the effect of Rooibos consumption on blood lipids and the endogenous antioxidant system during exercise (Hyunguk and Taesik, 2008). Twenty-eight male Sprague Dawley rats consumed Rooibos for 4 weeks while being subjected to exercise five days per week on a treadmill. Results showed that the antioxidant enzyme, SOD significantly increased in the exercise group and the exercise combined with the Rooibos group, but not in the rooibos-only group or the control group. Interestingly, the group that consumed the rooibos while concurrently exercising had a significantly lower amount of malondialdehyde in the blood.

When considering the human participant studies, one of the first to report on this is the study by Kim and Lim (2009), where they investigated the effects of Rooibos on male university soccer players during 12 weeks of endurance training in preparation for a tournament. Results showed that fermented Rooibos was consumed daily for 12 weeks to boost the endogenous antioxidant defence system/capacity by significantly increasing the antioxidant enzymes, SOD and GPx. The authors' recommendation included drinking Rooibos during the actual training process as part of the defence against oxidative stress induced by the strenuous training protocol. When considering green Rooibos, a study by Nagasawa and Kaori (2017) reported that the acute consumption of green Rooibos (520 mg) considerably increases the participants' biological antioxidant potential during high-intensity exercise. In a more recent study, Davies et al. (2019a) evaluated the effectiveness of fermented Rooibos as an ergogenic aid during physical activity while reporting on the plant's potential to reduce fatigue. Three standardised fermented Rooibos capsules (containing 340 mg rooibos polyphenols per capsule) were consumed daily for 4 weeks before a repeated exercise test. Results showed significantly improved elbow flexion peak torque and total work completed throughout five bouts of the exercise during the trial. In a similarly designed exercise study by Marnewick et al. (2016) reported on the effect of an acute dose (3 × 340 mg of rooibos polyphenols) of fermented rooibos consumed 90 min before the participants completed a muscular isokinetic strength fatiguing exercise regime. The elbow extension/flexion test on the Biodex (15 repetitions, 5 sets) generated muscle exhaustion. When comparing Rooibos to a placebo, the results for isokinetic strength performance revealed significantly higher total work, average power, and average peak torque during the second extension. In addition, Rooibos significantly reduced the levels of conjugated dienes at all 5-time points compared to the placebo and significantly increased the antioxidant capacity of the study participants. The daily consumption of standardised fermented Rooibos capsules decreased/mitigated the adverse symptoms and onset of acute mountain sickness and its related severe consequences on Aconcagua (6962 m) in a mountain climber observational

Table 1
Summary of human intervention studies with a focus on Rooibos, exercise and -related outcomes.

References	Study population	Number, Age (years), gender	Dosage	Study details	Main outcomes
Kim and Lim, 2009	University soccer players	Total n = 23 Parallel groups: 1: n = 8; 21.3 ± 2.4y 2: n = 8; 22.1 ± 2.8y 3: n = 7; 20.9 ± 1.5y Males	Chronic intake of 3g fermented Rooibos tea daily for 12 weeks	Randomised, placebo-controlled design with participants consuming fermented Rooibos tea (3g per 500 mL) during 12 weeks of endurance training	• The fermented Rooibos caused a significant ($P < 0.05$) increase in the antioxidant enzymes, GPx and SOD • No effect ($P > 0.05$) on the lipid (MDA) and DNA (8-OHdG) damage markers measured
Utter et al., 2010	College wrestlers	n = 23 19.4 ± 0.4y Males	An acute dose (6 % or 60 g l^{-1}) of Rooibos herbal tea	Randomised, cross-over controlled trial design, participants consumed fermented Rooibos, bottled water or a carbonated beverage to assess hydration after acute dehydration in collegiate wrestlers	• The fermented Rooibos beverage promoted rehydration similar to that of bottled water, with no significant differences between water and rooibos ($P > 0.05$)
Nagasawa and Murakami, 2017	Healthy adults	n = 10 20–22y Males	520 mg Green Rooibos Acute dose 30 min before exercise	Double-blinded, randomised cross-over, placebo-controlled performing 30-second sprint exercises	• Significantly ($P < 0.01$) increased antioxidant potential at both 3 and 30 mins after the exercise was completed • No significant ($P > 0.05$) difference was seen in the power output.
Marnewick et al., 2016	Healthy adults	n = 40 22.2 ± 4.3y Males	340 mg standardised fermented rooibos acute dose 90 min before exercise	Single blinded randomised cross-over, placebo-controlled trial design, with exercise test protocol entailing a maximal fatiguing elbow flexion/extension exercise including 5 sets of 15 all-out voluntary contractions separated by 10-second intervals on a Biodex System 3 at a speed of 60° per second	Performance outcomes were significantly ($P < 0.05$) higher in terms of the: • Total work ($P = 0.019$), as well as average power ($P = 0.021$) • Average peak torque greater ($P = 0.01$) during the elbow extension in the second (of five) exercise bouts when comparing rooibos with placebo
Davies et al., 2019a	Healthy adult's previous experience climbing high altitude	n = 8 46.6 ± 11.2y Males	340 mg fermented Rooibos three times daily during ascent	A case study based on a research expedition carried out on Aconcagua (6962 m) in the Andes Mountains of Argentina, was conducted to investigate the potential benefits of rooibos supplementation for sojourners at high altitude	• Using the Lake Louise Score, only negligible symptoms of acute mountain sickness were reported for seven of the men during and with reaching 6000 m
Davies et al., 2019b	Healthy adults	n = 32 22.2 ± 4.3y Males	340 mg fermented Rooibos 3 times daily for 4 weeks	Single blinded randomised cross-over, placebo-controlled trial design, with exercise test protocol entailing a maximal fatiguing elbow flexion/extension exercise including 5 sets of 15 all-out voluntary contractions separated by 10-second intervals on a Biodex System 3 at a speed of 60° per second	• Results showed the peak torque flexion (Nm) to be consistently higher ($P > 0.05$) in those that consumed the Rooibos daily • Similar results for the total work (joules) completed • These outcomes, although not significant, were noted as trends

research study (Davies et al., 2019a). The authors concluded that those who engage in leisure, tourist, and recreational activities, particularly in high-altitude settings, may benefit from consuming Rooibos as a potential prophylaxis, particularly for mountain sojourners and those ascending to high altitudes, as every year, more than 100 million tourists travel to high-altitude regions worldwide, with around 40,000 tourists attempting to climb Mount Kilimanjaro (5800 m) in Africa. Table 1 provides a more detailed summary of these human intervention studies. It is worth noting that all these reviewed studies on exercise/physical activities featured solely male participants, with none reporting on any female participants. This could be due to differences in skeletal muscle mass and hormonal responses to exercise between males and females (Accattato et al., 2017; Copetti et al., 2020). In an attempt to have a homogeneous study cohort, researchers often only recruit male participants, but this points to a major gap in the current literature.

As indicated by the human studies reviewed, (Table 1), Rooibos served as an excellent and unique dietary antioxidant source exhibiting promising potential ergogenic effects and mitigating exercise-induced oxidative stress as shown by enhancing the endogenous antioxidant defence system, significantly ($P < 0.05$) decreasing and/or delaying the onset of fatigue, inhibiting/reducing inflammatory responses and significantly ($P < 0.05$) improving certain exercise performance parameters (Watanabe et al., 2014; Nagasawa and Kaori, 2017; Davies et al., 2019a,b).

6. Conclusions and future direction

Incorporating Rooibos phytochemicals into a daily health routine is something one should consider if improved overall health and wellbeing is to be the focus. This may also be true in terms of the potential ergogenic properties of Rooibos to improve sports

performance and exercise outcomes. When Rooibos is consumed, it has demonstrated ability to modulate and strengthen the body's antioxidant defence system, thereby preventing and reducing damage caused by excessive RONS generated during strenuous exercise or physical activity. An increasing number of *in vivo* studies have also shown that consuming Rooibos increases plasma/serum total polyphenolic content, decreases oxidative lipid damage, boosts glutathione levels with a resultant enhanced GSH redox status, decreases pro-inflammatory cytokine levels, and improves exercise performance. Furthermore, it may serve as a prophylactic aid that would benefit athletes and people participating in high-altitude sports and/or leisure or recreational events such as climbing, trekking and hiking. However, the introduction of Rooibos into athletes' diets remains elusive, but has created "intriguing results and questions" that need to be further investigated. Currently, there is limited published literature on research pertaining to the interaction of exercise/physical activities and Rooibos, however, core findings from these studies provide a preliminary understanding and lays the groundwork for further research into this subject. Future focus should be on safety, optimal dosage, metabolic pathways and the role of genetic variations on an individuals' response to Rooibos consumption during different exercise/physical activity modalities/regimes. It is worth mentioning that all current literature in relation to human studies on exercise or physical activities and Rooibos, have not included female participants. Therefore, for inclusivity and generalisation of Rooibos for its purported antioxidant capacity and as a potential ergogenic aid, future research studies should aim to include female participants.

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Declaration of competing interest

All authors declare no conflict of interest. None of the governing bodies providing funding for this study have reviewed or provided input to the manuscript.

CRediT authorship contribution statement

Oiva Viety Kamati: Writing – review & editing, Writing – original draft, Conceptualization. **Simeon Davies:** Writing – review & editing, Conceptualization. **Roan Louw:** Writing – review & editing, Conceptualization. **Laura Bragagna:** Writing – review & editing, Conceptualization. **Karl-Heinz Wagner:** Writing – review & editing, Conceptualization. **Jeanine L Marnewick:** Writing – review & editing, Conceptualization.

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