



Review

# Multiple Biological Mechanisms for the Potential Influence of Phytochemicals on Physical Activity Performance: A Narrative Review

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**Abstract:** Natural phytochemicals (PCs) are responsible for the taste, colour, and aroma of many edible plants. Cohort studies have linked higher intake to a reduced risk of chronic degenerative diseases and premature ageing. The ability of foods rich in PCs, such as phythanthocyanins, apigenin, flavonols, flavonoids, bioflavonoids, gallic acid, ellagic acid, quercetin, and ellagitannins, to support physical activity has also been highlighted in a number of published pre-clinical and prospective clinical studies. This literature mostly emphasises the ability of PCs to enhance the adaptive upregulation of antioxidant enzymes (AEs), which reduces exercise-associated oxidative stress, but there are several other mechanisms of benefit that this narrative review addresses. These mechanisms include; protecting joints and tendons from physical trauma during exercise; mitigating delayed-onset muscle symptoms (DOMS) and muscle damage; improving muscle and tissue oxygenation during training; cultivating a healthy gut microbiome hence lowering excess inflammation; cutting the incidence of upper respiratory tract viral infections which disrupt training programmes; and helping to restore circadian rhythm which improves sleep recovery and reduces daytime fatigue, which in turn elevates mood and motivation to train.

**Keywords:** exercise; nutrition; phytochemicals; berries; physical activity; performance; oxidative stress; inflammation



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## 1. Introduction

There are multiple reasons why one person becomes an elite athlete whilst another may experience aches for days after a short jog. Genetic makeup, local facilities, family, and peer influence are key, but optimal nutrition plays a major role [1]. Adequate hydration, protein, carbohydrate, and mineral intake are essential, but more recently, interventions involving phytochemical-rich foods (PC-RFs) are increasingly being recognised as crucial for success for all physical activity programmes; whether it is a patient rehabilitating after illness, a novice looking to increase healthy exercise levels, a 'weekend warrior' hoping to beat their triathlon or parkrun time, or an elite sportsman dreaming of fame.

Boosting phytochemical intake may help individuals achieve the greatest benefit from exercise by targeting the important biochemical pathways that influence the ability to train stronger for longer [2]. Their unique properties have been shown to improve safety, comfort, and recovery whilst exercising, which in turn can improve motivation, enjoyment, enhance the health benefits of exercise, and ultimately performance [3]. The ability of PCs to enhance adapted oxidative stress enzymes is important, but there are many more fundamental attributes of some PC-RFs (Table 1) which, in summary, can be characterised as:

1. Ameliorating post-exercise oxidative stress pathways;
2. Protecting joints and tendons;
3. Reducing delayed-onset muscle symptoms and muscle damage;
4. Improving muscle and tissue oxygenation;
5. Improving gut health;
6. Helping to restore circadian rhythm, improve sleep, and reduce daytime fatigue;
7. Elevating mood and motivation to exercise;
8. Reducing viral colds and flu, which disrupt training.

### 1.1. Oxidative Stress and DNA Damage

Our DNA can be directly damaged by radiation, excess sun, and pollution or indirectly damaged by the formation of highly destructive reactive oxygen species (ROS). These ROS are produced naturally when the cell divides or makes energy for the body (as a by-product of oxidative phosphorylation). Excessive ROS are produced in situations where more energy is required, such as during strenuous exercise, particularly when an individual is unaccustomed to exercise or has conditions that require greater energy, such as obesity, chronic infection, chronic inflammation caused by poor diet, impaired gut health, or even psychological stress [4,5].

Damage to DNA can lead to mutations which, if they affect genes that regulate growth and other important biological pathways, lead to a host of age-related diseases, including atherosclerosis, cancer, heart disease, arthritis, diabetes, Alzheimer's disease, Parkinson's disease, cataracts, and macular degeneration [6–8]. In terms of exercise, excess cellular oxidative damage can increase fatigue, impair muscle and heart recovery, reduce endurance and muscle strength, and increase joint injuries, all of which decrease the ability to train regularly, lowering performance and fitness levels [4,5,9].

An estimated 10,000 potentially harmful breaks occur in our DNA every day. In response to this, humans, along with all living creatures, have developed a series of complex cellular defences, which mop up excess ROS and repair DNA. An important component of these is the AEs which absorb or donate electrons or protons that neutralise excess ROS. These include superoxide dismutase (SOD), catalase (CAT), glutathione-S-transferase (GST), and nitric oxide synthase (NOS).

After strenuous exercise, excessive quantities of ROS can overwhelm antioxidant enzyme capacity, and a state of tissue-damaging oxidative stress can occur. In response to this temporary state, an adaptive up-regulation of antioxidant genes occurs, which results in greater production of AEs [9]. This is one reason why it is important to gradually increase exercise levels over time, which allows the antioxidant levels to increase steadily [9–11]. Individuals with well-established exercise regimes and who follow adequate nutritional programmes have greater levels of AEs than sedentary individuals [9,10]. This not only accelerates recovery after exercise but also increases their defence against environmental and ingested oxidising carcinogens. This is one explanation as to why people who exercise regularly have a lower risk of cancer and other degenerative diseases [9–14].

This natural adaptive response can be impeded by nutritional deficiencies such as the essential minerals of Zn, Mg, Cu, and Se, which are required for antioxidant enzyme formation [15]. Likewise, oxidative stress can last longer if the diet is deficient in PCs, especially in elderly or overweight persons, where this adaptive process is known to be slower [10,16,17]. The ability of PCs to promote the natural adaptive process to ROS during exercise is via enhancing expression of Nuclear factor erythroid 2-related factor 2 (Nrf-2), the protein responsible for antioxidant enzyme production [18]. PCs also aid another aspect of cellular defence. After exercise, when ROS levels start to fall, Nrf-2 is degraded via binding and signalling from a protein called Kelch-like ECH-associated protein 1 (Keap1), and this avoids a situation where there are too few ROS. This situation, known as antioxidative stress, can also be harmful to cells as a certain level of ROS is required for normal functions such as regulating vascular tone, monitoring oxygen tension in the control of red cell production, and induction of stress response to pathogen attack [8,12,19–23].

PCs help with this degradation process of AEs, avoiding a state where too high a level AEs exist in the cells. So, the time that cells spend with an optimal oxidative balance is greatly helped by adequate PC intake, thus enhancing the safety and health benefits of exercise [8,12,14,16,20,21,23,24]. For this reason, the term *antioxidant* is misleading when referring to PC-RFs which improve antioxidant efficiency and capacity when needed and help to down-regulate it when not needed [8,12,14,16,20,21,23–25]. The same cannot be said for the direct antioxidants such as vitamins A, E, and N-acetylcysteine (NAC), which, unlike PCs, can actually impair antioxidant efficiency after exercise [26]. They can block antioxidant enzyme up-regulation after exercise, which leads to greater oxidative stress, and to such an extent that they can mitigate other health benefits of exercise and impede joint and tissue repair [8,12,16,20,21,23].

Vitamins A and E can also block Keap1, which interferes with the signal for Nrf2 to reduce the antioxidant levels after recovery from exercise. As such, they cause AEs to remain elevated, even when the oxidative stress subsides [12,16]. Combined with their ability to neutralise ROS by directly donating a hydrogen atom, this can result in the mopping up of too many ROS, leading to antioxidative stress [8,21,25,27–29]. This explains the findings of a study involving kayakers who were randomised to take a vitamin E and  $\beta$ -carotene supplement. They demonstrated that although antioxidant status was reduced immediately after exercise, muscle damage and inflammation were worse, hindering the recovery of muscle damage [20]. In another randomised study, performance increased following pomegranate extract administration, but then the benefit was negated if it was taken with the direct antioxidant NAC [30]. There were even some concerns with vitamin C, essential for tissue repair, reported in another study which demonstrated that when taken in high doses, it decreased muscle mitochondrial biogenesis and hampered training-induced oxidative adaptations, impairing endurance performance [31].

Reassuringly, there is no statistically robust study that has shown that PC-RFs cause diseases or reduce exercise performance [32]. Quite the opposite, as numerous clinical studies have reported wide-ranging health and exercise benefits from boosting intake of whole foods such as pomegranate, chamomile, and citrus sinensis fruit which are particularly rich in important PCs including phytoanthocyanins, apigenin flavonols, flavonoids, bioflavonoids, gallic acid, ellagic acid, quercetin, and ellagitannins [30,33–35]. This evidence also includes boosting the diet with nutritional whole, phytochemical-rich food supplements [30,32,36–38].

### 1.2. Protection of Joints and Tendons

Although exercise and stretching support long-term joint health, joint stiffness after exercise can last for several days preventing retraining, especially after contact sports, running, or cycling [39]. This temporary, negative effect on joints can be a strong demotivating factor that can put people off regular training [40,41]. Fortunately, curcuminoids in turmeric, apigenin in chamomille, ellagic acid, and quercetin, and resveratrol (found in tea, grapes, polygonum cuspidatum root, and pomegranate) downregulate excess tissue chronic inflammation by reducing cyclooxygenase-2 (COX-2) activation of prostaglandins [42]. This is why they help to reduce post-exercise joint pains, but unlike anti-inflammatory pain killers, they also reduce oxidative damage, block matrix metalloproteinase (MMPs) enzymes responsible for extracellular matrix (cartilage) degeneration, reduce anti-apoptotic effects on chondrocytes, and promote repair and regeneration of cartilage, all of which improve joint health and help prevent long-term degenerative arthritis [43–46]. Moreover, they do not adversely affect kidney function, increase blood pressure, or cause indigestion. On the contrary, these foods protect the heart and help protect gastric mucosa [47]. Resveratrol, pomegranate, and turmeric have an additional role as prebiotics that improve gut health and integrity, reducing the absorption of pro-inflammatory toxins into the systemic circulation, which would otherwise further trigger joint damage (see sections below).

Although much of this mechanistic data comes from animal studies, numerous intervention studies of concentrated, wholefood capsules have demonstrated clinically mean-

ingful benefits for discomfort and long-term joint health over placebo and non-steroidal anti-inflammatory medications [48–50]. In one notable clinical study, young female volunteers were randomly assigned to take chamomile extract or placebo and undertake exhaustive treadmill exercise on a negative slope which puts more pressure on the knees whilst running. They found that the formal pain scale in the chamomile group was significantly reduced after each run compared with the control group [51].

### 1.3. Delayed Onset Muscle Soreness (DOMS)

DOMS is a sore, aching, painful feeling in the muscles after unfamiliar and unaccustomed intense exercise, which most of us have experienced from time to time. The discomfort is due to temporary muscle damage and inflammation [2]. Having some DOMS is usually a positive sign post-exercise, and usually, muscle heals into a stronger state than it was before the activity [52]. The level of DOMS usually diminishes following subsequent exercise sessions, providing that the intensity is gradually increased and that there is a good nutritional status. However, in some situations, the onset of muscle soreness following exercise is not solely due to the myofibrillar damage from the initial exercise, as a secondary injury state can occur [53]. In this situation, the body overreacts to this muscle damage, triggering an inflammatory cascade that further damages muscle, especially in people who tend to have excessive inflammation. This secondary muscle damage delays re-training and thereby reduces performance [53]. This discomfort may be so intense for some individuals that it puts them off attending training and rehabilitation programmes [40].

Sportsmen and women have adopted various strategies to reduce the severity and duration of DOMs, including massage, acupuncture, and ice baths [54]. Nutritional interventions are gaining scientific credibility, especially those involving PC-RFs, as there is an increasing body of evidence demonstrating that specific blends of PCs can work in synergy to reduce this secondary, excess inflammation, thereby preventing further muscle damage [55–58]. In one randomised study, for example, turmeric was provided to athletes exercising intensively, resulting in a reduction of the accumulation of advanced glycation end-products in muscle tissue and improved muscle regeneration and performance in the long term [59,60]. In another study involving turmeric capsules, researchers reported a reduction in the biological markers of inflammation after exercise-induced muscle damage and improved functional capacity during subsequent exercise sessions [42]. Pomegranate extract was provided to recreationally active males in a double-blind, placebo-controlled, crossover, randomised design, and those randomised to the pomegranate group reported significantly attenuated weakness and reduced soreness of the elbow flexor muscles [61]. Likewise, pomegranate extract provided to elite weightlifters reduced post-exercise soreness, accelerated muscle recovery, and ameliorated the capacity to adhere to an intensive training programme [62]. The other PC-RFs which have been shown to reduce post-exercise muscle pain include blackberries, blueberries, and Moreno cherries, but more recently, the muscle-relaxing properties of chamomile have been of scientific interest to researchers [35,53,63–65].

### 1.4. Improved Nitric Oxide Production and Oxygen Utilisation

As mentioned above, unlike antioxidant vitamins, PCs do not over-deplete intracellular oxygenative species, especially the beneficial nitric oxide (NO). They also promote the conversion of nitrates in meat into NO, which otherwise would have been combined with protein to form carcinogenic nitrosamines [66]. NO has been shown to have many roles in the body, including triggering vasodilation of arteries which increases muscle, heart, and brain tissue perfusion and oxygenation, lowers excess blood pressure, and improves mood [67–69]. It is likely that the same mechanism explains why regular intake of NO-rich foods such as celery, pomegranate, beetroot, and spinach is linked to lower dementia risks [70].

Relevant to exercise, NO-rich foods are known to help the muscles to restore their functionality and increase the efficiency of oxygen usage [30,37]. A number of studies

have demonstrated that boosting intake with supplementation also improves muscle oxygenation, increases the time to fatigue, reduces finish times for endurance exercisers, and increases power amongst weightlifters [33,62,71–77]. In other studies, PC-RF supplementation has been shown to improve 60%  $\dot{V}O_2$  max during exercise, increase aerobic capacity compared to controls, reduce post-exercise fatigue, and accelerate recovery both in untrained and elite athletes [78,79]. Volunteers who took a green tea extract for 8 weeks had oxygenated haemoglobin and myoglobin levels (a marker of increased skeletal muscle aerobic capacity) [80]. Hesperidin, a bioflavonoid found in citrus fruit, improved endothelial function (via increased NO availability), inhibited excess ROS production, decreased plasma levels of pro-inflammatory markers, and improved exercise outcomes in cyclists, including power, speed, and energy [81]. For elite and recreational athletes, hesperidin was found to be an ergogenic aid to enhance muscle recovery between training sessions, optimise oxygen and nutrient supply to the muscles, and improve anaerobic performance [82].

### 1.5. Improving Gut Health

The billions of symbiotic bacteria which contribute to the gut microflora and microbiome as a whole is increasingly being recognised as an important factor for exercise performance, as well as avoiding chronic disease both within and outside of the gut [83,84]. Some PCs, such as ellagitannin found in pomegranate and curcumin found in turmeric, act as prebiotics to healthy bacteria, which helps improve gut health and bowel wall integrity [85–87]. Resveratrol in grapes and polygonum cuspidatum root also enhances the formation of a protective biofilm over healthy bacteria such as *Lactobacillus paracasei*, facilitating adhesion, aggregation, and colony formation of these healthy variants [88,89]. Curcuminoids, which are poorly absorbed in the small bowel, pass into the colon where they promote the local synthesis of AEs, protecting probiotic bacteria from oxidative damage [89]. In return, probiotic bacteria help the breakdown of PCs into more readily absorbed and more bioactive varieties. These bioactive phytochemicals not only reduce gut inflammation directly but help the growth of anti-inflammatory commensal bacteria. A gut wall with less oxidative damage and lower inflammation functions better with greater integrity and more efficient immune surveillance. A healthier gut wall reduces the absorption of proinflammatory toxins into the systemic circulation, thereby avoiding excess systemic inflammation [86,90,91]. Relevant to exercise, studies have shown that enhancing the diet with a prebiotic supplement helps improve mobility and physical independence in the elderly, as well as immunity both against infection and circulating cancer cells [85]. Certainly, better gut health is associated with better physical fitness, and although validation studies are required, various international bodies agree that there is a role for probiotics to achieve this during training [92–94]. Runners with better gut health are less prone to exercise-induced diarrhoea and are less prone to respiratory infections [95,96]. People with a healthy gut have better vitamin D absorption and are less prone to osteoporosis, a particular risk factor for dedicated and professional cyclists [96]. Low vitamin D is associated with higher levels of unregulated hyperinflammatory cytokine production [97].

### 1.6. Helping Restore Circadian Rhythm, Improving Sleep, and Reducing Day Time Fatigue

Lack of sleep impacts multiple biological pathways, which negatively affects health and well-being, particularly day-time fatigue, emotional regulation, cognitive performance, and quality of life [98,99]. After exercise, it is important to aim for a good night's sleep as it is an integral part of muscle repair, physical recovery, and enhancement of the adaptive process, which occurs between bouts of exercise. In addition, muscle-building chemicals such as human growth hormone (HGH) are naturally produced by the body in the deep stages of sleep [100]. Clinically, improved sleep quality reduced the risk of both injury and illness in athletes, not only optimising health but also potentially enhancing performance and competitive success through increased participation in training [72,101]. Despite this, most studies have found that athletes often fail to obtain the recommended amount of sleep, threatening both performance and health [101]. Athletes face a number of obstacles

that can reduce the likelihood of obtaining proper sleep, such as muscle and joint soreness, competition schedules, travel, stress, academic demands, and overtraining. In light of this, people embarking on an exercise programme require more careful monitoring and intervention to promote proper sleep to improve both performance and overall health. The first step for exercisers who find it difficult to reach the state of deep sleep is the adoption of practical sleep hygiene rules [99]. The most important of these are the lifestyle strategies that support the circadian rhythm, the biological processes which relax the mind and dampen down the body's metabolism in preparation for sleep, in order for the body and mind to know when it is time to sleep and when it is time to wake up [102–104]. PCs such as citrus bioflavonoids, resveratrol, and quercetin in pomegranate have been reported to aid sleep by supporting the body's circadian rhythm [36,105]. In particular, boosting the intake of chamomile to levels well above that achieved from food or drink, especially combined with resveratrol, although not directly sedating, helps to induce a state of calm and a relaxed frame of mind, which combine to help reduce negative thoughts at bedtime, a common barrier to falling asleep and wakefulness throughout the night [106–112].

### *1.7. Reducing Stress and Elevating Mood and Motivation to Exercise*

Exercise is one of the most important and effective strategies to improve mood [113] and is proven to enhance clinical outcomes in people with depression and other mental illnesses [114,115]. However, a concerning paradigm exists, having a low mood decreases enthusiasm, demotivates people to exercise and is linked to poor adherence to continuing exercise and rehabilitation programmes [40,41]. Multiple approaches have been investigated to encourage people to exercise, including trying to elevate mood and reduce discomfort during exercise [40,41,114]. The mood-elevating and anti-inflammatory properties of phytochemical-rich supplements have been evaluated in several studies and have been found to be a convenient way to improve motivation and comfort, both during and after exercise [40,111,112,116]. In particular, resveratrol and chamomile have been found to work in synergy to lower stress and improve mood, putting both men and women in a better frame of mind to exercise [117]. Likewise, chamomile extract consumption has been shown to reduce anxiety in young male karate players before a competition [118].

### *1.8. Anti-Viral Properties: Avoiding Breaks in Training from Colds and Flu*

Although moderate exercise increases immunity, more intense regimens can cause temporary dips in immunity, increasing the risk of viral infections [4,119]. Upper respiratory tract viral infections are a significant cause of breaks in training and can result in the cancellation of a much-anticipated sporting event [120,121]. As well as being uncomfortable, intense exercise during a cold or flu infection is unwise as it can be associated with acute virus-induced skeletal and heart muscle damage, so it is not wise to train during the infective period [120].

Unlike steroidal and non-steroidal painkillers, the ability of PCs to suppress pro-inflammatory cytokines does not lead to reduced viral immunosurveillance [4]. In fact, the opposite effect occurs. Resveratrol, for example, has been reported to increase anti-viral cytotoxic T lymphocytes and natural killer immune cells [122]. Likewise, apigenin, derived from chamomile, has been shown to induce anti-viral activity in T-immune cells [123]. In addition to these protective immune mechanisms, PCs have recently been discovered to have direct anti-viral properties in laboratory studies [123–127]. This explains the results of recent clinical studies which reported a combination of pomegranate, turmeric, citrus, chamomile, and resveratrol-accelerated recovery from a COVID-19 infection and prevented the development of long COVID-19 by enhancing viral elimination and reducing viral-associated inflammatory tissue damage [128,129].

**Table 1.** Classification of PCs and examples of food sources [15].

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<b>Polyphenols</b>
1. Flavonoids
Flavonols: quercetin, kaempferol (onions, kale, leeks, broccoli, red grapes, tea, apples)
Flavones: apigenin, luteolin (celery, herbs, parsley, chamomile, rooibos tea, capsicum pepper)
Isoflavones: genistein, daidzein, glycitein (soya, beans, chick peas, alfalfa, peanuts)
Flavanones: naringenin, hesperetin (citrus fruit)
Anthocyanidins (red grapes, blueberries, cherries, strawberries, blackberries, raspberries, tea)
Flavan-3-ols (tannins): catechins, epicatechin, epigallocatechin gallate (tea, chocolate, grapes)
Flavanolols: silymarin, silibinin, aromadedin (milk thistle, red onions)
Dihydrochalcones: phloridzin, aspalathin (apples, rooibos tea)
2. Phenolic acids
Hydrobenzoic acids: gallic acid, ellagic acid, vanillic acid (rhubarb, grapes, raspberries, blackberries, pomegranate, vanilla, tea)
Hydroxycinnamic acids: ferulic acid, P-coumaric acid, caffeic acid, sinapic acid (wheat bran, cinnamon, coffee, kiwi fruit, plums, blueberries)
3. Other non-flavonoid polyphenols
Other tannins (cereals, fruits, berries, beans, nuts, wine, cocoa)
Curcuminoids: curcumin (turmeric)
Stilbenes: cinnamic acid, resveratrol (grapes, wine, blueberries, peanuts, raspberries)
Lignans: secoisolariciresinol, enterolactone, sesamin (grains, flaxseed, sesame seeds)

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<b>Terpenoids</b>
1. Carotenoid terpenoids
Alpha, beta and gamma carotene (sweet potato, carrots, pumpkin, kale)
Lutein (corn, eggs, kale, spinach, red pepper, pumpkin, oranges, rhubarb, plum, mango, papaya)
Zeaxanthin (corn, eggs, kale, spinach, red pepper, pumpkin, oranges)
Lycopene (tomatoes watermelon, pink grapefruit, guava, papaya)
Astaxanthin (salmon, shrimp, krill, crab)
2. Non-carotenoid terpenoids
Saponins (chickpeas, soya beans)
Limonene (the rind of citrus fruits)
Perillyl Alcohol (cherries, caraway seeds, mint)
Phytosterols: natural cholesterol, siosterol, stigmasterol, campesterol (vegetable oils, cereal grains, nuts, shoots, seeds, seed oils, whole grains, legumes)
Ursolic acid (apples, cranberries, prunes, peppermint, oregano, thyme)
Ginkgolide and bilobalide (Ginkgo biloba)

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<b>Thiols</b>
Glucosinolates: isothiocyanates (sulforaphane), dithiolthiones (cruciferous vegetables; broccoli, asparagus, Brussel sprouts, cauliflower, horseradish, radish, mustard)
Allylic sulfides: allicin and S-allyl cysteine (garlic, leeks, onions)
Indoles: Indole-3-carbinol (broccoli, brussel sprouts)

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<b>Other PCs</b>
Betaines found in beetroot
Chlorophylls found in green leafy vegetables
Capsaicin found in chilli
Peperine found in black peppers

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## 2. Conclusions

It is now well established that a phytochemical-rich diet helps in the maintenance of an optimal oxidative balance, reduces excess and inappropriate inflammation, and improves gut health, all of which are vital to healthy longevity and the avoidance of chronic degenerative disease [16,32,128]. They improve the ability to exercise by avoiding muscle and joint damage by improving tissue oxygenation and recovery. For many amateur sportsmen and women, this can improve a sense of self-worth and satisfaction when exercising, thereby enhancing their incentive to exercise regularly [4,38]. Regular exercise, in turn, is one of the most important self-help lifestyle strategies to maintain well-being, improve mood, happiness, independence, body shape, and avoidance of the five most

common causes of premature death in Western-style societies; cancer, stroke, heart disease, diabetes, and dementia [130,131].

There are several ways in which phytochemical intake can be increased, most obviously, eating a wider array and higher quantity of dark green vegetables such as spinach, broccoli, and cabbage; fruits such as apples, pomegranate, blackcurrants, grapes, cranberries, and raspberries; mushrooms; aromatic herbs, spices, teas, and nuts. Table 1 summarises some of the more common phytochemicals and their food sources, and a diet incorporating a wide assortment of these foods would ensure a good level and variety of PCs [15]. Juices and smoothies will further concentrate phytochemical levels, but this can remove the bulk, and will increase the glycaemic index (GI) and free sugar content [132]. Concentrating dried phytochemical-rich whole foods into a capsule could be a convenient way to supplement total intake and spread it across the day without affecting the GI, and condensing these whole foods does not usually reduce PC content in the drying process [133]. It would be useful that future studies of PC-RF, concentrated whole food supplementation, or possibly extracted phytochemicals address the various mechanisms of potential benefit in supporting exercise regimens, in addition to oxidative pathways, in their evaluation [74,133]. It would also be helpful if future studies address the relative impact of boosting phytochemicals before and after exercise in specific groups such as the elderly, those with pre-existing higher stress levels, and joint or gut issues.

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