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REVIEW

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The effect of dietary anthocyanins on biochemical, physiological, and subjective exercise recovery: a systematic review and meta-analysis

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ABSTRACT

Anthocyanins (ACN), the sub-class of (poly)phenols responsible for the red-blue-purple pigmentation of fruit and vegetables, have gained considerable interest in sport and exercise research due to their potential to facilitate exercise recovery. A systematic literature search was performed using PubMed, The Cochrane Library, MEDLINE, SPORTDiscus and CINAHL. Thirty nine studies were included and the standardized mean difference (Hedges *g*) for creatine kinase (CK), anti-oxidative and inflammatory markers, strength, power and delayed onset muscle soreness (DOMS) indices were pooled in separate meta-analyses; meta-regression was also performed on reported ACN dose. Immediately post-exercise there was an increase in antioxidant capacity (*g*: 0.56) and reduced C reactive protein (*g*: -0.24) and tumor necrosis factor α (*g*: -40); $p \leq 0.02$. Strength was improved with ACN at all time points (*g*: 0.45–0.67). DOMS (*g*: -0.23) was lower 24 hours post-exercise and power was improved 24 hours (*g*: 0.62) and 48 hours (*g*: 0.57) post exercise. The CK was lower 48 hours post-exercise (*g*: -0.31) and there was a trend for a positive association with ACN dose (p = 0.057). This systematic review provides new data showing ACN-rich foods promote functional and subjective recovery likely due to the antioxidant and anti-inflammatory properties of ACN.

Introduction

Physical exercise places a degree of mechanical and metabolic stress on the body, which both contribute to a common pathological response involving oxidative stress and inflammation (Pyne 1994). Exercise induced muscle damage (EIMD) is typically characterized by an initial insult followed by a secondary inflammatory response, which is more prominent following eccentric actions (Bongiovanni et al. 2020). The EIMD has more immediate implications, including delayed onset muscle soreness (DOMS) and impaired muscular strength and power, which have the ability to compromise performance and quality of training (Clarkson, Nosaka, and Braun 1992; MacIntyre, Reid, and McKenzie 1995). Although the mechanisms and time course can differ, both mechanical and metabolic stress can cause an increase in the appearance of intracellular proteins in the blood (e.g., creatine kinase: CK) potentially due to disruptions in calcium homeostasis from a loss of cell membrane integrity (Brancaccio, Maffulli, and Limongelli 2007; Tee, Bosch, and Lambert 2007). In addition, exercise also induces signaling cascades, largely orchestrated by reactive oxygen and nitrogen species (RONS), transcriptional release of pro-inflammatory cytokines (e.g., tumor necrosis factor alpha [TNF- α] and interleukin-6

Anthocyanins; antiinflammatory; antioxidant; berries; exercise recovery; muscle soreness; strength

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[IL-6]), and acute phase proteins, e.g., C-reactive protein; CRP (Ebbeling and Clarkson 1989; Pyne 1994) and an increase in these immunological markers are thought to be associated with muscle soreness, loss of muscle function as well as overtraining and fatigue (Gleeson et al. 1995; Hecksteden et al. 2016; MacIntyre, Reid, and McKenzie 1995). Given the potential for physiological stress associated with strenuous exercise and the potential for compromised training and/or competition performance due to loss of strength and power and muscle soreness that can last for several days, there has been a strong emphasis to identify natural recovery strategies (Bongiovanni et al. 2020; Howatson and van Someren 2008).

Amongst the available strategies, dietary interventions, particularly fruit, have gained considerable attention when it comes to improving recovery following EIMD (Doma et al. 2021; Naderi et al. 2018). Fruit could influence the recovery process because they contain (poly)phenols which could interact with the secondary cascade associated with EIMD, via their antioxidant and anti-inflammatory properties (Bowtell and Kelly 2019; Pereira Panza, Diefenthaeler, and da Silva 2015). However, not all fruit is equal in terms of (poly)phenolic content and abundance and certain fruit might be more beneficial for exercise recovery. For example, in a simple

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KEYWORDS

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

meta-analysis of 25 studies of fruit on recovery from EIMD, berries were reported to have the greatest overall effect (Doma et al. 2021). Berries are rich in anthocyanins (ACN), a subclass of (poly)phenols, responsible for the red-blue-purple pigmentation in fruits (Manach et al. 2004; Pérez-Jiménez et al. 2010). These compounds have gained much research interest due to their propensity to maintain the balance between the oxidative and anti-oxidative systems and reduce inflammatory cytokines (Wang et al. 1999). In vitro ACN have been shown to act as more potent antioxidants as compared to some other (poly)phenols (Pojer et al. 2013) and to exhibit anti-inflammatory actions similar or superior to nonsteroidal and other anti-inflammatory drugs (Pereira Panza, Diefenthaeler, and da Silva 2015; Seeram et al. 2001). Additionally, ACN might supress pain at both an enzymatic (e.g., cyclooxygenase) and transcriptional (e.g., nuclear factor kappa beta) level (Pojer et al. 2013; Seeram et al. 2001). Moreover, cyanidin-3-glucoside, a common ACN found in berries (Sandoval-Ramírez et al., 2020), has been shown to up-regulate the expression of transcriptional pathways related to muscle function and reduce fatigue in rodent models (Hu et al. 2020; Matsukawa et al. 2017). Other benefits include the potential for ACN to enhance blood flow that might aid the removal of waste products and muscle metabolites (Keane et al. 2016b; Rodriguez-Mateos et al. 2019). Recently, Bloedon et al. (2019) reported that ACN-rich whole foods reduce exercise-induced oxidative stress and inflammation, but the effect on muscle soreness and functional (e.g., strength and power) recovery, which are arguably more important measures of exercise recovery (Byrne, Twist, and Eston 2004; Damas et al. 2016; Torres et al. 2012), were not reported. Therefore whilst there is some evidence that ACN might be beneficial in facilitating recovery, the narrative nature of these reviews or lack of attention to the potential active compounds or other aspects of recovery means the conclusions are not quantitively derived or based on a complete picture of the available work (Bloedon et al. 2019; Doma et al. 2021; Harty et al. 2019; Naderi et al. 2018; Owens et al. 2019; Vitale, Hueglin, and Broad 2017). Therefore, the aim of this study was to synthesize and evaluate the effects of anthocyanin-rich foods on biochemical, physiological, and subjective indices of exercise recovery in human trials.

Methods

Search strategy

A systematic literature search of the following electronic bibliographic databases: PubMed and The Cochrane Library as well as searching MEDLINE, SPORTDiscus, and CINAHL via EBSCOhost was carried out from inception until August 2020. The search strategy (Supplementary material) was conducted using Medical Subject Heading (MeSH) and Boolean operations devised using two key concepts (1) anthocyaninrich foods and (2) exercise recovery. Furthermore, the reference list of retrieved literature reviews was hand-searched to find potential articles that could be included in the systematic review.

Study selection

The inclusion criteria were as follows: (1) randomized controlled trials; (2) in healthy adult participants (average age ≥18 years) regardless of training status; (3) included anthocyanin-rich foods [blackberry, blackcurrant, blueberry, black elderberry, black grape, cherry, chokeberry, rhubarb, strawberry, red wine, plum (Manach et al. 2004; Pérez-Jiménez et al. 2010) or other red-blue-purple berries only where the ACN content was reported] given before exercise (could continue administration after); (4) had a placebo or suitable control; (5) reported haematological markers, functional (e.g., strength or power) or subjective (e.g., visual analogue scales or pain pressure threshold) recovery measures following exercise. For comparability, only similar biomarkers were included in the meta-analysis, these were; creatine kinase (CK) antioxidant (total antioxidant capacity/status), inflammatory (IL-6, TNF- α or CRP) or oxidative stress (thiobarbituric acid reactive substances; TBARS), antioxidant enzyme activity [superoxide dismutase (SOD) and glutathione peroxidase (GPx)], strength (maximal voluntary contractions; MVC), power (counter movement jumps; CMJ) and visual analogue scales or Likert scales for DOMS.

Exclusion criteria were non-adult, smoker or diseased participants, animal and in vitro studies. Studies were also excluded if anthocyanins are given alongside another intervention (i.e., pharmacological agent or dietary supplement; other juice or fruit to increase palatability could be included as long as anthocyanin content was reported) and no appropriate control or reference groups could be identified. Titles and abstracts were independently reviewed by two researchers (RK and CH) to evaluate their eligibility for inclusion in this review. Only full texts that were published in English or had an existing translation were retrieved and examined.

Data extraction and quality assessment

The study data was extracted into pre-piloted forms by the main reviewer (RK) and checked for accuracy by a second reviewer (KJ). Any discrepancies were resolved by reviewing the original article. The following data was extracted from each study: the first author's last name(s), publication date, funding source, participants characteristics, sample size, supplement type, ACN content, dosing strategy and duration, any dietary restrictions, wash out period and type of exercise (metabolic, mechanical or combined], outcome time points, outcome measures, mean ± SD of the outcomes specified above were also extracted. Where necessary data was extrapolated from figures and graphs and authors were contacted to provide missing data (Abbott et al. 2020; Hurst et al. 2019; Hurst et al. 2020; McCormick et al. 2016; Morehen et al. 2021), if they did not respond within 1 week a follow up was sent, those who did not reply within a month were excluded (e.g., Beals et al. 2017; Lamb et al. 2019) for variables where data could not be obtained. A modified PEDro scale (de Morton 2009) was used to assess the methodological quality of the selected studies. One point could be awarded for each the original 11 items as well as additional items thought to be relevant to the study design.

Additional criteria were as follows (1) the study acknowledged whether or not they received funding; (2) compliance to the intervention was reported; (3) ACN content was reported in the supplement either according to the manufacturer's nutritional label or confirmed by analysis in the study; participants refrained from taking antioxidant and anti-inflammatory drugs and supplements (4) before and/or (5) during study (6) sample size calculation was included. In studies where a cross-over design an additional item was included "(7) a minimum 7-day washout between trial treatments." Thus, a total of 17 points could be awarded for parallel studies and 18 for crossover studies. For parallel studies a score of <7, 7-10, 11-14, and 15-17 and for crossover studies <8, 8-11, 12-15, and 16-18 was poor, fair, good and excellent, respectively (Doma et al. 2021). Risk of bias was also assessed according to Cochrane Collaboration guidelines and is represented graphically to indicate the overall quality of all studies (Higgins and Green 2011).

Statistical analysis

Standardized mean differences (SMD) were calculated using Hedge's g using independent groups and for parallel studies and paired groups for crossover studies (Borenstein et al. 2019). To calculate the standard deviation within groups for crossover studies the correlation between pairs of observations (r; which was calculated from studies where individual data was provided (Hurst et al. 2019; McCormick et al. 2016) and assumed to be 0.5 (Amiri et al. 2019; Doma et al. 2021; Higgins and Green 2011)) was included. Both study designs were included in an inverse random effects metaanalysis (due to study design heterogeneity) using Stata v.16.0 (StataCorp, College Station, Texas, USA) sub-grouped by study design to determine whether the inclusion of crossover designs influenced the SMD (Supplemental information (Higgins and Green 2011)). Where there were sufficient studies (Jackson and Turner 2017) separate meta-analyses were conducted for immediately post (≤ 2 h), 24 hours post and 48 hours post exercise. For studies that reported measures over several time points, the data were only analyzed for the most recent in that time interval. Hurst et al. (2019) reported different doses so these were pooled to get an overall ES before inclusion in the meta-analysis (Higgins and Green 2011). If DOMS was measured at different sites, the largest ES was included in the meta-analysis.

Secondly, sensitivity analysis was performed by omitting one study at a time to evaluate the potential bias and robustness of the overall SMD. Heterogeneity between studies was determined by the I² statistic. For the I² statistic, I² values $\leq 25\%$, $\leq 50\%$, $\leq 75\%$, and >75% indicated no, little, moderate, and significant heterogeneity, respectively. To identify potential sources of heterogeneity, moderator analysis was performed using sub-group analysis for categorical variables including training status, exercise type and study duration. In addition, where ACN content was reported a meta-regression was conducted on the most reported variables (MVC, DOMS and CK). Potential publication bias for each outcome was evaluated by Egger's test (p < 0.10) and visual inspection of funnel plots (Begg and Mazumdar 1994). Where publication bias was detected, trim and fill analysis was conducted (Steichen 2010). The SMD were interpreted as small (>0.2), moderate (>0.5) and (\geq 0.8) large (Sullivan and Feinn 2012) and a Z effect p < 0.05 was considered significant.

Results

Literature search and study characteristics

The search results are presented in Figure 1, following full search and exclusion of irrelevant articles 39 articles were included in this review. A total of 27 independent group studies and 12 crossover studies with 767 participants were included in this review (Table 1). Of the interventions used tart cherry was the most common (18 studies). Other studies used blackcurrant (6 studies), grape (6 studies), blueberry (3 studies), chokeberry (3 studies), bilberry (1 study), plum (1 study) and one a mixed anthocyanin cocktail. The duration of the studies varied greatly with some investigating the acute influence (1-2 h before), most investigating the shortterm influence (2-10 days) and some the longer-term influence (20 days-8 weeks) of ACN. Most studies were in trained individuals and the median age was 24 (range 18-48) years. The median ACN content, where reported, was 80 (range 8-3600) mg/day. The quality of studies was rated as poor (n = 1), fair (n = 8), good (n = 19), excellent (n = 11; Table 1). The risk of bias is presented in Figure 2, which showed the percentage of studies with low, medium and high risk of bias for each domain. The main potential sources of bias came from allocation, blinding of the intervention or did not acknowledged whether they received funding (other bias).

The influence of ACN on recovery

Immediately post exercise there was an increase in TAC (SMD: 0.56; 95% CI: 0.09, 1.03; p = 0.02; $I^2 = 61.7\%$) with ACN. ACN also resulted in a moderate reduction in SOD (SMD: -0.42; 95% CI: -0.77, -0.07, p = 0.02), TNF- α (SMD: -0.40; 95% CI: -0.72, -0.07, p = 0.02) and a small reduction in CRP (SMD: -0.24; 95% CI: -0.43, -0.06, p = 0.01) at immediately post-exercise, with no heterogeneity $(I^2 = 0.0\%)$. At 24 hours, SOD remained lower (SMD: -0.46; 95% CI: -0.88, -0.03; I² = 16.3%) with ACN. Intake of ACN reduced DOMS at 24 hours (SMD-0.23; 95% CI: -0.40, -0.06; p < 0.01; $I^2 = 0.0\%$). Strength (MVC) was increased immediately post-exercise (SMD: 0.45; 95% CI: 0.14, 0.75; $I^2 = 0.0\%$), 24 hours post (SMD: 0.50; 95% CI: 0.18, 0.82; $I^2 = 60.3\%$) and greatest at 48 hours post (SMD: 0.67; 95% CI: 0.32, 1.02; $I^2 = 65.4\%$). At 24 hours power (CMJ) was also increased with ACN (SMD: 0.62; 95% CI: 0.01, 1.24; p = 0.047; $I^2 = 66.6\%$). At 48 hours CMJ (SMD: 0.57; 95% CI: 0.04, 1.11; p = 0.04; $I^2 = 63.9\%$) and CK were lower (SMD: -0.31 95% CI: -0.55, -0.08; p < 0.01; $I^2 =$ 12.8%). Sensitivity analysis suggested stable results for these



Figure 1. PRISMA flow diagram of included studies: there were 1111 studies identified by the search strategy, 769 non-duplicated records. After screening the titles and abstracts, 62 of the records were deemed potentially eligible for inclusion and full texts were retrieved for further evaluation. Twenty-five articles were excluded and a further 2 found from hand searching, leaving 39 included studies.

variables (Supplemental material). There was no influence of ACN on any other variables (Figure 3).

Subgroup analysis, publication bias and meta-regression

Subgroup analysis is presented in Table 2. Immediately post-exercise ACN increased TAC and decreased SOD, only in metabolically biased exercise. IL-6 was also reduced by metabolic-type exercise immediately post and 48 hours post exercise. MVC was improved immediately post-exercise with mechanically damaging exercise, whereas 24 hours post and 48 hours post there was a large effect for exercise that had a combined mechanical and metabolic component. CRP was lower immediately post exercise, DOMS at 24 hours post exercise and CK at 48 hours post-exercise with combinedtype exercise. MVC was improved immediately post-exercise and 24 hours post-exercise in trained and untrained individuals, but only 48 hours post-exercise in trained participants. CRP was lower immediately post-exercise in trained individuals, whereas in the untrained participants IL-6 was lower. Twenty-four hours post-exercise TNF α and IL-6 was lower in untrained, whereas trained participants had lower SOD and DOMS at 24 hours and CK at 48 hours.

Studies of a shorter duration decreased CRP immediately post-exercise and improved MVC and DOMS 24 hours post and CK and CMJ 48 hours post. Studies of a longer duration Increased TAC and reduced SOD, TNF α and CK immediately post. TAC remained higher at 48 hours and TBARS and TNF α were reduced in the longer duration studies. There was evidence of publication bias for TBARS (p = 0.001) and DOMS (p = 0.009) immediately post-exercise.

Table 1. Study characte	eristics of	f included studies.								
	Study			Mean					Dietary	Study
Author	design	Participants	<i>n</i> (m/f)	age (y)	Supplement	ACN (mg)	Dosing	Exercise	restrictions $^{\rho}$	quality
Pilaczynska-Szczesniak et al. (2005)	Ы	Well trained male rowers	ACN:9 CTL:10	21 22	Chokeberry juice	3450	$3 \times 50 \text{ mL}$ for 4 wks	Incremental rowing test 40% max increased by 10 % each 3 mins to 90%	z	Good
Connolly, McHugh, and Padilla- Zakour (2006)	9	Male College students	14	22	Tart cherry juice	80	2 × 12 oz 8 days (Exercise day 4) 6 day wash out	2 sets of 20 maximal eccentric contractions of the elbow	z	Good
Skarpańska-Stejnborn, Basta, and Pilaczyńska- Szrześniak (2006)	E	Well trained male rowers	ACN:10 CTL: 9	20 21	Blackcurrant capsules	250 of BC	$3 \times 326\text{mg}$ capsules for 6 wks	2000m rowing TT	z	Fair
Sadowska-Krepa et al. (2008)	III	Healthy males	ACN:9 CTL: 5	22 21	Red grape powder	41	$3 \times 390 \text{ mg}$ capsules for 6 wks	300m swim test starting at 70- 75% and last 50m at maximal effort	z	Poor
Lyall et al. (2009)	9	Healthy individuals	5/5	48	Black currant capsules	240	4 capsules (2 pre and 2 post exercise) 21 dav wash out	30-min row at 80% VO _{2max}	z	Good
Howatson et al. (2010)	ЫI	Recreational runners	ACN: 7/3 CTI : 6/4	37 38	Tart cherry juice	80	2×236 mL for 8 days (Exercise day 6)	Marathon	z	Good
Kuehl et al. (2010)	ЫI	Recreational runners	ACN: 19/7 CTI · 15/10	38	Tart cherry juice	80	2×355 mL for 8 days (Exercise	3 running segments of relay race (26.3 + 2.5 km)	z	Good
Skarpańska-Stejnborn et al. (2010)	Ы	Well trained male rowers	ACN: 10 CTL: 12 CTL: 12	20 21 21	Black grape extract	38.5	$3 \times 367 \mathrm{mg}$ capsules for 6 wks	Incremental rowing test 40% max increased by 10 % each 3 mins to 90%	z	Fair
Bowtell et al. (2011)	9	Well-trained male athletes	10	28	Tart cherry juice	547	2 × 30 mL for 10 days (Exercise day 8) 14 day wash out	10 sets of 10 single-leg knee extensions at 80% of their 18M	z	Fair
McAnulty et al. (2011)	ЫI	Trained	ACN: 13 CTI : 12	31 33	Blueberries		250g for 6 wks and 375 g 1 hour hefore	2.5h treadmill run	۲	Good
McLeay et al. (2012)	8	Recreationally trained females	10	22	Blueberry smoothie	193	(3 × 200g blueberries on day of exercise) 200g each day 2 days after exercise 30 day wash out	3 sets of 100 eccentric knee extensions	~	Fair
O'Connor et al. (2013)	ЫI	Untrained	ACN: 10/10 CTI · 11/9	20	Grape powder	8	46g for 45 days	3 sets of 6 reps eccentric elbow flevion at 120% 1RM	z	Excellent
Kastello et al. (2014)	8	Untrained	4/10	21	Tart cherry tablet	200	2× tablet for 20 days (Exercise day 16) 16 dav wash out	5 sets of 10 reps of maximal arm contractions	~	Fair
Bell et al. (2014)	PII	Well trained male cyclists	ACN: 8 CTL: 8	30	Tart cherry juice	546	2×30 mL for 7 days (Exercise day 5-7)	High intensity simulated cycling road race 109 min	۲	Excellent
Silvestre et al. (2014)	9	Male triathletes	9	44	Black grape juice		66g of grape concentrate 21 day wash out	10 km cycling, 6 km running in sand and 1.5 km swimming at sea	z	Fair
Skarpańska-Stejnborn et al. (2014)	ЫI	Well trained male rowers	ACN: 10 CTL: 9	21 21	Chokeberry juice	3600	3 imes 50 mL for 8 wks weeks)	2000m rowing TT	z	Good
Bell et al. (2015)	Ы	Well trained male cyclists	ACN: 8 CTL: 8	30	Tart cherry juice	546	$2 \times 30 \text{ mL}$ for 8 days (Exercise day 5)	High intensity simulated cycling road race 109 min	7	Excellent
Levers et al. (2015)	Ы	Resistance-trained males	ACN: 11 CTL: 12	21 21	Tart cherry capsules	66	1 × 480 mg capsule for 10 days (Exercise day 8)	10 sets of 10 reps of a barbell back squat at 70% 1-RM	z	Excellent
Toscano et al. (2015)	PII	Recreational runners	ACN: 11/4 CTL: 11/2	43 36	Grape juice	53 mg/L	2×5 mL/kg for 28 days (Exercise day 26)	Time to exhaustion at anaerobic threshold	Z	Good
Bell et al. (2016)	PII	Trained soccer players		25	Tart cherry juice	73.5			٢	Good

Interfact Disk Z × 30 m day 5, 10, 10 days (Exercise Sector Under Sector N Good Tart cheny upute 819 9 0mL for 6 days Simulated water polo N N Cool Tart cheny upute 819 9 0mL for 6 days Simulated water polo N N Cool Tart cheny juice 819 9 0mL for 6 days Simulated water polo N N Cool Chokebeny juice 819 9 0mL for 6 days Simulated water polo N N Cool Blabeny juice 819 2 × 30 for 12 days (Exercise Repetitive minum effort N Cool Bluebeny juice 810 2 × 30 for 12 days (Exercise Repetitive and sill sesions and sill s		-	-		ACN: 8 CTL: 8		-		2 × 20 mL for 7 days (Exercise day 5)	Adapted LIST 90 min	-	
Tart cherry capsules 66 1 capsule for 10 days (Exercise Bailt mining canton N Excellent Tart cherry juice 819 9mL for 6 days Simulated wate polo N 660 Choleberry juice 1 15 (0mL of chokeberry juice Training canton N 660 Tart cherry powder 64 2 × 30 g for 12 days (Exercise Repetitive maximal effort N 660 Biberry juice 80 2 × 30 g for 12 days (Exercise Repetitive maximal effort N 660 Biberry juice 81 7 × 500mL for 8 days (Exercise Repetitive maximal effort N 660 Biberry juice 33 2 × 300 for 12 days (Exercise Repetitive maximal effort N 660 Biberry juice 335 2 × 500 Lior 8 days (Exercise Repetitive maximal effort N 660 Biberry juice 332 2 × 500 Lior 8 days (Exercise Repetitive maximal power 7 660 Biberry juice 735 2 × 500 Lior 8 days (Exercise 8m meanining statt a 80% of 0m N 660 Biberry juice	PII Untrained ACN: 1/7 20 CTL: 2/6 21	Untrained ACN: 1/7 20 CTL: 2/6 21	Intrained ACN: 1/7 20 CTL: 2/6 21	ACN: 1/7 20 CTL: 2/6 21	20 21		Blackcurrant nectar	151.4	2×455 mL for 8 days (Exercise on day 5)	3 sets of 10 reps of eccentric contractions using a bar weighted with 115% of 1RM	z	Good
Tart cherry juice B19 gam fie 6 days 35 day vash out for 4 wis Stady vash out match 60 min N Good Chokeberry juice 1 1 × 100mL of chokeberry juice Taring camp; a combination of for 4 wis N Good Tart cherry powder 64 2 × 30 g for 12 days (Exercise Repetitive, mainlen effort N Good Bilberry juice 80 2 × 30 g for 12 days (Exercise Repetitive, mainlen effort N Good Bilberry juice 80 2 × 500mL for 8 days (Exercise Repetitive, mainlen effort N Good Bilberry juice 33 2 × 500mL for 8 days (Exercise equation of the quadrecose intersity and for a medicare intersity and for medicare intersity and so for equations and s × N Good Buckurmant extract 33 × 24 g for 4 days (Exercise day and 10 m decreter intersity and to medicare intersity and to medicare intersity and to medicare intersity and so for equations and s × N Good Buckurmant extract 33 × 24 g for 4 days (Exercise day and 10 m decreter intersity and 30 % N N Good Buckurmant extract 33 × 3 g m moderate intersity d	PII Endurance trained runners ACN: 8/3 21 CTL:10/ 6 22	Endurance trained runners ACN: 8/3 21 CTL:10/ 6 22	ndurance trained runners ACN: 8/3 21 CTL:10/ 6 22	ACN: 8/3 21 CTL:10/ 6 22	21 22		Tart cherry capsules	99	1 capsule for 10 days (Exercise dav 8)	Half marathon	z	Excellent
Chokebenry Juice 1 × 100 mL of chokebenry Juice Training trace acombination of N N Good Tart cherry powder 64 2 × 30 g for 12 days (Exercise Repetitive, mainlarel effort N Coold Biberry Juice 80 2 × 30 g for 12 days (Exercise Repetitive, mainlarel effort N Coold Biberry Juice 80 2 × 500 mL for 8 days (Exercise Repetitive, mainlarel effort N Coold Biberry Juice 80 2 × 500 mL for 8 days (Exercise day Repetitive, mainlarel effort N Coold Bibueberry powder 53.2 2 × 500 mL for 8 days (Exercise day Rem treadmil time trial Y Coold Bibueberry powder 73.3 2 × 30 mL for 8 days (Exercise day Rem treadmil time trial Y Coold Tart cherry Juice 73.3 2 × 30 mL for 8 days (Exercise day Sem treadmil time trial Y Coold Bibueberry powder 73.3 2 × 30 mL for 8 days (Exercise day Sem treadmil time trial Y Coold Bibueberry powder 73.3 0.8 m treadmil time trial Y Coold	CO Well trained male water- 9 19 polo plavers	Well trained male water- 9 19 polo players	Vell trained male water- 9 19	9 19	19		Tart cherry juice	819	90 mL for 6 days 35 day wash out	Simulated water polo match 60 min	z	Good
Cart cherry powder 64 2 × 30 g for 12 days (Exercise day 5) Repetitive contractions of the quadrices N Excellent Bilberry Juice 80 2 × 200 mL for 8 days (Exercise day 6) Half mathon N Good Jun nectar 335 2 × 50 mL/kg for 28 days Exercise and speed estination N Good Jun nectar 335 2 × 50 mL/kg for 28 days Exercise day and goderate intersions a week for 4 weeks N Good Jun tectar 335 2 × 30 mL for 8 days (Exercise day 4) Bkm treadmli time trial Y Good Jurble grape juice 735 2 × 30 mL for 8 days (Exercise day 4) Bkm treadmli time trial Y Good Urple grape juice 735 2 × 30 mL for 8 days (Exercise day 5) 15 × 30 m maximal spints with and 10 m deceleration phase Y Good Jurble grape juice 735 2 × 30 mL for 8 days (Exercise day 5) 15 × 30 m maximal spints with and to maximal spints with 15 × 30 m maximal spints with 13 × 30	PII Male handball players ACN:8 19 0 CTL: 7 18	Male handball players ACN:8 19 0 CTL: 7 18	lale handball players ACN:8 19 0 CTL: 7 18	ACN:8 19 0 CTL: 7 18	19 (0 18	0	chokeberry juice		1×100 mL of chokeberry juice for 4 wks	Training camp: a combination of aerobic, strength and conditioning twice per day, lasting 3 h in total	z	Good
Bilberry juice B0 2 × 300mL for 8days (Exercise Hait marathon N Good Plum nectar 335 2 × 5mL/kg for 28 days Training camp: 3 × 60 min N 6 ood Plum nectar 335 2 × 5mL/kg for 28 days Training camp: 3 × 60 min N 6 ood Blueberry powder 33 24 g for 4 days (Exercise day Rain moderate intensity and opered sessions and 5 × strength and sell sessions a Y 6 ood Tart cherry juice 735 3 × 24 g for 4 days (Exercise day Rm treadmill time trial Y 6 ood Purple grape juice 735 2 × 30mL for 8 days (Exercise day Rm treadmill time trial Y 6 ood Blackcurrant extract 584 0 mg/kg 1 h before exercise 30min row at their predicted Y 6 ood Blackcurrant extract 1312 1.6 mg/kg 1 h before exercise 30min row at their predicted Y 6 ood Blackcurrant extract 240 0.8 mg/kg 1 h before exercise 30min row at their predicted Y 6 ood Blackcurrant extract 240 3.2 mg/kg 1 h before exercise 30min row at their pre	PII Recreationally active ACN: 9/6 26 CTL: 10/4 25	Recreationally active ACN: 9/6 26 CTL: 10/4 25	ecreationally active ACN: 9/6 26 CTL: 10/4 25	ACN: 9/6 26 CTL: 10/4 25	26 25		Tart cherry powder	64	2 × 30 g for 12 days (Exercise day 5)	Repetitive, maximal effort isokinetic concentric/eccentric contractions of the quadriceps until the fatique	z	Excellent
Plum nectar 53.5 2 × 5mU/kg for 28 days Training camp: 3 × 60 min and orderate intensity and moderate intensity and and desistons and spouse and species day and sub- day 5) N Good Tart cherry juice 73.5 2 × 30 mL for 8 days (Exercise day 5) 15 × 30 m maximal sprints with a week for 4 weeks and species day and species day N 6 ood Purple grape juice 73.5 2 × 30 mL for 8 days (Exercise day 5) 15 × 30 m maximal sprints with a readmill running test at 80% of rapid 10 m deceleration phase N 6 ood Blackcurrant extract 58.4 0.8 mg/kg 1 h before exercise 30 min row at their predicted 70% V0 _{2max} Y 6 ood Blackcurrant extract 2.4 0.3 mg/kg 1 h before exercise 30 min row at their predicted 70% V0 _{2max} Y 6 ood Tart cherry juice 8 2 × 30 mL for 5 days (Exercise day 5) 3 onmin row at their predicted 70% V0 _{2max} Y 6 ood Mixed plum, blueberry, rapperry and caraberry rapperry and caraberry readmetry 5 sets of 10 reps maximal 70% V0 _{2max} Y 6 ood Mi	PII Recreationally ACN: 8/3 31 trained runners CTL: 8/2 31	Recreationally ACN: 8/3 31 trained runners CTL: 8/2 31	ecreationally ACN: 8/3 31 trained runners CTL: 8/2 31	ACN: 8/3 31 CTL: 8/2 31	31 31		Bilberry juice	80	$2 \times 200 \text{ mL}$ for 8 days (Exercise day 6)	Half marathon	z	Good
Blueberry powder 3×24 gfor 4 days (Exercise day 8km treadmill time trial Y Good Tart cherry juice 735 $2 \times 30 \text{ m}$ to 10 4 day wash out 10×14 day wash out $10 \times 10 \times$	PII Well trained male ACN:12 19 handball players CTL: 13	Well trained male ACN:12 19 handball players CTL: 13	vell trained male ACN:12 19 handball players CTL: 13	ACN:12 19 CTL: 13	19		Plum nectar	53.5	2×5 mL/kg for 28 days	Training camp: 3 × 60 min sessions of general strength and moderate intensity endurance 2× maximal power and speed sessions and 5× strength and skill sessions a week for 4 weeks	z	Good
Tart cherry juice 73.5 2 × 30 mL for 8 days (Exercise day 5) 15 × 30 mL for 8 days (Exercise apid 10m deceleration phase N Good Purple grape juice 10 mL/kg (2h before exercise) Treadmill running test at 80% of 7 day wash out N Excellent Blackcurrant extract 58.4 0.8 mg/kg 1h before exercise 30min row at their predicted Y Good Blackcurrant extract 131.2 1.6 mg/kg 1h before exercise 30min row at their predicted Y Good Blackcurrant extract 240 3.2 mg/kg 1h before exercise 30min row at their predicted Y Good Blackcurrant extract 131.2 1.6 mg/kg 1h before exercise 30min row at their predicted Y Good Tart cherry juice 3 2 × 30 mL for 5 days (Exercise day 6 mont and wat their predicted Y Good Tart cherry juice 8 2 × 30 mL for 5 days (Exercise 5 sets of 10 reps maximal Y Excellent Mixed plum, 58 2 × 30 mL for 5 days (Exercise day 5) 5 sets of 10 reps maximal Y Excellent Mixed plum, 58 2 × 30 mL for 5 days (Exercise day 5) 30 min at 70% of their VO _{2max} N Good Mixed plum, 58 2 × 30 mL for 8 days (Exercise day 5) 30 min at 70% of their VO _{2max} N Good </td <td>CO Recreational runners 24 31</td> <td>Recreational runners 24 31</td> <td>ecreational runners 24 31</td> <td>24 31</td> <td>31</td> <td></td> <td>Blueberry powder</td> <td></td> <td>3 × 24 g for 4 days (Exercise day 4) 10-14 day wash out</td> <td>8km treadmill time trial</td> <td>~</td> <td>Good</td>	CO Recreational runners 24 31	Recreational runners 24 31	ecreational runners 24 31	24 31	31		Blueberry powder		3 × 24 g for 4 days (Exercise day 4) 10-14 day wash out	8km treadmill time trial	~	Good
Purple grape juice10 mL/kg (2 h before exercise)Treadmill running test at 80% of NNExcellentBlackcurrant extract58.40.8 mg/kg 1 h before exercise30min row at their predictedYGoodBlackcurrant extract131.21.6 mg/kg 1 h before exercise30min row at their predictedYGoodBlackcurrant extract131.21.6 mg/kg 1 h before exercise30min row at their predictedYGoodBlackcurrant extract131.21.6 mg/kg 1 h before exercise30min row at their predictedYGoodTart cherry juice2 × 30 mL for 5 days (Exercise day30min row at their predictedYGoodTart cherry juice82 × 30 mL for 5 days (Exercise dayCompetitive rugby union matchNFairTart cherry juice82 × 30 mL for 5 days (Exercise5 sets of 10 reps maximalYExcellentMixed plum,582 × 30 mL for 5 days (Exercise5 sets of 10 reps maximalYExcellentblueberry,882 × 30 mL for 5 days (Exercise5 sets of 10 reps maximalYExcellentblueberry,582 × 30 mL for 8 days (Exercise30 min at 70% of their VO _{2max} NGoodblueberry,582 × 30 mL for 8 days (Exercise5 sets of 10 reps maximalYExcellentcontractions of the82 × 30 mL for 8 days (Exercise5 sets of 10 reps maximalYExcellentblueberry,582 × 30 mL for 8 days (Exercise30 min at 70% of their VO _{2max} NGoodf	PII Trained female dancers ACN: 10 19 CTL: 10 CTL: 10	Trained female dancers ACN: 10 19 . CTL: 10	rained female dancers ACN: 10 19 . CTL: 10	ACN: 10 19 7 CTL: 10	19		Tart cherry juice	73.5	2 × 30 mL for 8 days (Exercise day 5)	$15 \times 30 \text{ m}$ maximal sprints with a rapid 10 m deceleration phase	z	Good
Blackcurrant extract 58.4 0.8 mg/kg 1 h before exercise 30min row at their predicted Y Good 70% VO _{2max} 16 mg/kg 1 h before exercise 30min row at their predicted Y Good Blackcurrant extract 131.2 1.6 mg/kg 1 h before exercise 30min row at their predicted Y Good Blackcurrant extract 240 3.2 mg/kg 1 h before exercise 30min row at their predicted Y Good Tart cherry juice 2 30 mL for 5 days (Exercise day Competitive rugby union match N Fair Tart cherry juice 8 2 × 30 mL for 5 days (Exercise day Competitive rugby union match N Fair Tart cherry juice 8 2 × 30 mL for 5 days (Exercise day contractions of the elbow flexor N Good Mixed plum, 58 2 × 30 mL for 5 days (Exercise day voluntary eccentric N Good Mixed plum, 58 2 × 240 mL 8 days (Exercise day 30 min at 70% of their VO _{2max} N Good Mixed plum, 58 2 × 240 mL 8 days (Exercise day 30 min at 70% of their VO _{2max} N Good Mineberry, randberry, 30 min at	CO Recreationally 14 39 trained runners	Recreationally 14 39 trained runners	ecreationally 14 39 trained runners	14 39	39		Purple grape juice		10 mL/kg (2 h before exercise) 7 day wash out	Treadmill running test at 80% of their VO _{2max} until exhaustion.	z	Excellent
Blackcurrant extract 131.2 1.6 mg/kg 1 h before exercise 30min row at their predicted Y Good Tart cherry juice 240 3.2 mg/kg 1 h before exercise 30min row at their predicted Y Good Tart cherry juice 2< × 30 mL for 5 days (Exercise day	PII Healthy individuals ACN: 8 44 CTL: 8 42	Healthy individuals ACN: 8 44 CTL: 8 42	ealthy individuals ACN: 8 44 CTL: 8 42	ACN: 8 44 CTL: 8 42	42 44		Blackcurrant extract	58.4	0.8 mg/kg 1 h before exercise	30min row at their predicted 70% VO _{2max}	~	Good
Blackcurrant extract 240 3.2 mg/kg 1 h before exercise 30min row at their predicted Y Good Tart cherry juice 2 × 30 mL for 5 days (Exercise day 70% VO _{2max} N Fair Tart cherry juice 3 × 30 mL for 5 days (Exercise day Competitive rugby union match N Fair Tart cherry juice 8 2 × 30 mL for 5 days (Exercise 5 sets of 10 reps maximal Y Excellent Mixed plum, 58 2 × 30 mL for 5 days (Exercise 5 sets of 10 reps maximal Y Good Mixed plum, 58 2 × 240 mL 8 days (Exercise 5 sets of 10 reps maximal Y Good Mixed plum, 58 2 × 240 mL 8 days (Exercise running downhill (-15%) for N Good maquiberry, maquiberry, 30 min at 70% of their VO _{2max} N Good tart cherry juice 2 × 30 mL for 8 days (Exercise Lunning downhill (-15%) for N Good	PII Healthy individuals ACN: 8 44 CTL: 8 42	Healthy individuals ACN: 8 44 CTL: 8 42	ealthy individuals ACN: 8 44 CTL: 8 42	ACN: 8 44 CTL: 8 42	44 42		Blackcurrant extract	131.2	1.6 mg/kg 1 h before exercise	30min row at their predicted 70% VO _{2max}	~	Good
Tart cherry juice 2 × 30 mL for 5 days (Exercise day Competitive rugby union match N Fair 3) Wash out not reported 3) Wash out not reported 5 sets of 10 reps maximal Y Excellen Tart cherry juice 8 2 × 30 mL for 5 days (Exercise 5 sets of 10 reps maximal Y Excellen Mixed plum, 58 2 × 30 mL 8 days (Exercise 5 sets of 10 reps maximal Y Excellen Mixed plum, 58 2 × 240 mL 8 days (Exercise running downhill (-15%) for N Good Mixed plum, 58 2 × 240 mL 8 days (Exercise running downhill (-15%) for N Good maquiberry, 70% of their VO _{2max} 30 min at 70% of their VO _{2max} N Good fart cherry juice 2 × 30 mL for 8 days (Exercise LIST N Fair	PII Healthy individuals ACN: 8 44 CTL: 8 42	Healthy individuals ACN: 8 44 CTL: 8 42	lealthy individuals ACN: 8 44 CTL: 8 42	ACN: 8 44 CTL: 8 42	44 42		Blackcurrant extract	240	3.2 mg/kg 1 h before exercise	30min row at their predicted 70% VO _{2max}	~	Good
Tart cherry juice 8 2 × 30 mL for 5 days (Exercise 5 sets of 10 reps maximal Y Excellent Mixed plum, 58 2 × 240 mL 8 days (Exercise 5 sets of 10 reps maximal Y Excellent Mixed plum, 58 2 × 240 mL 8 days (Exercise running downhill (-15%) for N Good mageuiberry, 30 min at 70% of their VO _{2max} 30 min at 70% of their VO _{2max} N Good randberry cranberry 2 × 30 mL for 8 days (Exercise LIST N Fair	CO Well-trained male rugby 10 28 union players	Well-trained male rugby 10 28 union plavers	Vell-trained male rugby 10 28 union players	10 28	28		Tart cherry juice		$2 \times 30 \text{ mL}$ for 5 days (Exercise day 3) Wash out not reported	Competitive rugby union match	z	Fair
Mixed plum, 58 2 × 240 mL 8 days (Exercise running downhill (-15%) for N Good blueberry, and day 5) 30 min at 70% of their VO _{2max} maquiberry, raspberry and cranberry concentrates 2 × 30 mL for 8 days (Exercise LIST N For	PII Untrained males ACN: 12 24 ⁻ CTL: 12 24	Untrained males ACN: 12 24 ⁻ CTL: 12 24	Intrained måles ACN: 12 24 ⁻ CTL: 12 24	ACN: 12 24 ⁻ CTL: 12 24	24 24		Fart cherry juice	ω	2 × 30 mL for 5 days (Exercise day 5)	5 sets of 10 reps maximal voluntary eccentric contractions of the elbow flexor	~	Excellent
Tart cherry juice $2 \times 30 \text{ mL}$ for 8 days (Exercise LIST N Fair day 6)	PII Untrained males ACN: 15 22 CTL: 15 23	Untrained males ACN: 15 22 CTL: 15 23	Intrained males ACN: 15 22 CTL: 15 23	ACN: 15 22 CTL: 15 23	22 23		Mixed plum, blueberry, maquiberry, raspberry and cranberry concentrates	28	2 × 240 mL 8 days (Exercise day 5)	running downhill (-15%) for 30 min at 70% of their VO _{2max}	z	Good
	PII Team-sport players ACN: 4/6 28 CTL: 4/6 25	Team-sport players ACN: 4/6 28 CTL: 4/6 25	eam-sport players ACN: 4/6 28 CTL: 4/6 25	ACN: 4/6 28 CTL: 4/6 25	28 25		Tart cherry juice		$2 \times 30 \text{ mL}$ for 8 days (Exercise day 6)	LIST	z	Fair

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Table 1. Continued.										
	Study			Mean					Dietary	Study
Author	design	Participants	<i>n</i> (m/f)	age (y)	Supplement	ACN (mg)	Dosing	Exercise	restrictions $^{\rho}$	quality
Abbott et al. (2020)	9	Well trained male soccer players	10	19	Tart cherry juice		$2 \times 30 \text{ mL}$ for 3 days (Exercise day 1)	Competitive soccer match	۶	Good
							14-28 day wash out			
Costello et al. (2020)	ЫI	Recreational runners	ACN: 6/4	30	Blackcurrant extract	110	$2 \times$ capsules for 10 days (Exercise	Half marathon	z	Excellent
			CTL: 6/4	29			day 8)			
Hurst et al. (2020)	PII	Healthy individuals	ACN: 17	38	Blackcurrant extract	240	$2 \times$ capsules for 5 weeks	30min row at their predicted	7	Excellent
			CTL: 17	38				70% VO _{2max}		
Morehen et al. (2021)	8	Well trained male rugby	11	18	Tart cherry juice	640	2×30 mL for 7 days (Exercise day	Competitive rugby league match	z	Good
		league players					6)			
							5 day wash-out			
Abbreviations: anthocy	/anin (AC	V); Blackcurrant (BC); Cross-ov	ver (C); Loughbc	orough inte	srmittent shuttle test (Ll	ST); Parallel (ł	PII), Repetitions (reps) $^{ ho}$ apart from e	xclusion of the product under inve	tigation.	

So too were TAC, CMJ and MVC (p < 0.058) 24 and 48 hours post exercise and IL-6 (p = 0.004) 48 hours post-exercise. No other publication bias was detected. Trim and fill analysis was done for the above variables resulting in lower DOMS immediately post-exercise (SMD: -0.33; 95% CI: -0.60, -0.06) higher CMJ at 24 hours (SMD: 0.47; 95% CI: 0.12, 0.81) and increased TAC at 48 hours post-exercise (SMD: 0.35; 95% CI: 0.04, 0.67). With trim and fill analysis CMJ was no longer significantly higher at 48 hours (SMD: 0.18; 95% CI: -0.10, 0.47), but there was no other materially different SMDs. Meta-regression suggested a trend for a weak positive association with ACN dose and CK (Figure 4) at 48 hours (p = 0.057; $I^2 = 0\%$), however there was no relationship with MVC or DOMS or CK at any other time point.

Discussion

The present study represents the most comprehensive picture that synthesizes and evaluates the effects of dietary ACN on exercise recovery from all the available literature including additional analyses that consider ACN dose, exercise type, training status, and study duration. These new data showed a beneficial effect for ACN on biochemical, physiological, and subjective recovery following exercise up to and including 48 hours post-exercise.

Dietary intake of ACN resulted in an increase in total antioxidant capacity/status immediately post exercise, which was mirrored by a reduction in SOD at the same point which was still reduced 24 hours post exercise, suggesting less reliance on these defence systems over time due to the ability of the ACN to scavenge free radicals (Skarpańska-Stejnborn, Basta, and Pilaczyńska-Szcześniak 2006). Dietary ACN have antioxidant potential due to the ability for hydrogen (electron) donation and the positively charged oxygen in the flavonoid molecule (Bi et al. 2014). Moreover, the time course aligns with plasma maximum concentrations of ACN and their metabolites, which typically occurs 1-2 hours after ingestion (Hurst et al. 2019; Keane et al. 2016a). In accordance, a number of studies included in this analysis that measured these indices gave an acute dose preexercise that would coincide with the peak plasma concentrations (de Lima Tavares Toscano et al., 2020; Hurst et al. 2019; Hurst et al. 2020; Lyall et al. 2009; McAnulty et al. 2014; Silvestre et al. 2014). Interestingly, the antioxidant effects of ACN were predominantly seen in exercise with a major metabolic component, which might be attributable to greater exercise-induced oxidative stress owing to higher oxygen consumption during the exercise, whereas a delayed and prolonged generation of RONS after mechanically strenuous eccentric exercise is likely (Fisher-Wellman and Bloomer 2009), because of the secondary inflammatory-mediated damage that occurs after exercise (Howatson and van Someren 2008; Owens et al. 2019; Bongiovanni et al. 2020).

The consumption of ACN resulted in reduced CK at 48 hours post, and inflammation (TNF α and CRP) to be reduced immediately post-exercise. As there is an inherent interplay between these markers and RONS (Baird et al. 2012; Lee and Clarkson 2003), the early antioxidant actions



Figure 2. Risk of bias of included studies.



Figure 3. Summary forest plot of findings for anthocyanin (ACN) intake on exercise recovery relative to a control immediately post (top), 24 hours post (middle) and 48 hours post (bottom) exercise. Data missing for timepoint if less than 5 studies (N/A). For maximal voluntary contraction (MVC), countermovement jump (CMJ) and total antioxidant capacity/status (TAC) right side favors ACN. For interleukin 6 (IL-6), tumor necrosis factor alpha (TNF α), C-reactive protein (CRP), thiobarburic acid reactive substances (TBARS), creatine kinase (CK), superoxide dismutase (SOD) and glutathione peroxidase (GPx), and delayed onset of muscle damage (DOMS) left side favors ACN (n = number of studies, I² statistic for heterogeneity).



Figure 4. Bubble plot with fitted meta-regression for creatine kinase (CK) at 48 h post exercise.

of the ACN represent one potential mechanism that might supress the efflux of CK (through reduced cell membrane disruption) and inflammatory indices. The anti-inflammatory properties of ACN are well documented (Fallah et al. 2020; Speer et al. 2020), and might relate to their ability to interact with cellular enzymes and signaling pathways (Li et al. 2017). For example, ACN have been shown to reduce inflammatory enzymes such as cyclooxygenase and lipoxygenase (Kirakosyan et al. 2018; Wang et al. 1999), which might be mediated by their ability to inhibit mitogen-activated protein kinase and nuclear factor kappa beta pathways (Pojer et al. 2013). Dependent on exercise modality, intensity and duration CK has been shown to peak 24-72 hours after exercise (Baird et al. 2012). Whereas an acute inflammatory response due to immunological activation typically occurs more rapidly (1-4 hours) and a second wave of inflammation is detectable in a similar timeframe to peak CK (Peake et al. 2017). A lower peak in the CK and inflammatory indices might reflect a reduction in muscle damage and also indicate a faster recovery after exercise with ACN compared to a control. While this might relate to the antioxidant capacity of the ACN it could also be because of improved blood flow and clearance (Baird et al. 2012; Rodriguez-Mateos et al. 2019). Other meta-analyses have not suggested an effect of fruit or (poly)phenols on CK (Doma et al. 2021; Hill et al. 2021), it should be acknowledged there are several criticisms of CK as a marker for muscle damage especially owing to its high inter and intra-individual variability and its meaningfulness as a recovery index (Brancaccio, Maffulli, and Limongelli 2007; Hill et al. 2021; Warren, Lowe, and Armstrong 1999). However, some included studies in the current review found a benefit of ACN-rich foods (Carvalho et al. 2018; (Lyall et al. 2009) and an ACN rich cocktail on exercise-induced CK (Lima et al. 2019) it therefore might be that some (poly)phenols such as ACN are more beneficial than others. Moreover, the large number of pooled studies at 48 hours post exercise might account for some of the variability, where the participant numbers amounted to 244.

The aforementioned supports the notion that ACN improves biomarkers related to exercise recovery. However, the influence on symptoms such as functional (i.e., strength and power) and muscle soreness indices perhaps are better representations of recovery facilitation and EIMD (Byrne, Twist, and Eston 2004; Damas et al. 2016; Torres et al. 2012). There was an effect of ACN on reducing DOMS at 24 hours and recovery of strength loss 0, 24 and 48 hours post exercise, whereas power was only increased 24 and 48 hours post-exercise. Reduced strength loss, and recovery of strength, was greater with ACN, initially for eccentrically biased exercise, but CMJ and MVC were improved 24 hours and 48 hours post-exercise after combined metabolic and mechanically strenuous exercise. Both mechanical and metabolic exercise increase RONS due to mitochondrial oxygen consumption, the increased circulating catecholamines, elevated participation of eccentric muscle contraction-induced damage, inflammatory response and/or the intermittent and repeated sprint actions that can cause temporary ischemicreperfusion in the skeletal muscle (Ascensão et al. 2008; Leeuwenburgh and Heinecke 2001). Strength loss after exercise has been proposed to be related to oxidative stress (Cakir-Atabek, Dokumaci, and Aygün 2019), whereas loss in muscle power might be more synonymous with DOMS and the inflammatory response (Byrne, Twist, and Eston 2004). Speculatively, the early increase in antioxidant capacity with ACN might help to reduce strength loss, whereas the recovery in power coincides with the reduced DOMS at 24 hours post-exercise. These data are of great interest because therapeutic recovery interventions (e.g., massage, cold water immersion and compression garments) have shown some benefits in recovery of DOMS, strength and power, but there are limited data to suggest that all facets of recovery can be affected in a positive manner (Brown et al. 2017; Davis, Alabed, and Chico 2020; Leeder et al. 2012). Whereas, in this review, ACN-rich foods are shown to improve physiological and subjective recovery following strenuous exercise and hence should be an integral consideration for practitioners and exercisers to consider in their diet.

Notwithstanding, there are several limitations within the included studies that warrant discussion. Firstly, studies with a crossover study design were included in the meta-analysis and these could be influenced by the repeated bout effect (RBE) between experimental trials. The RBE refers to the protective effect afforded by a single bout of eccentric-biased muscle actions that provide a protective effect on subsequent bout of exercise (even if this is performed on the contralateral limb) and hence could mask any treatment effect (Howatson and van Someren 2007). However, including crossover studies did not appear to add to heterogeneity to the results (Figure 3). Secondly, some studies which investigated the effects on functional and subjective recovery after "real" game play (Abbott et al. 2020; Kupusarevic, McShane, and Clifford 2019; Morehen et al., 2021); while these arguably have good application they are heavily confounded by the RBE as well as other recovery practices that might be conducted concurrently. Conversely, some studies used

								Sub	group						
				Exercise type				Trainin	ig stat	SN:		Study	y durā	ation	
Variable		Metabolic	2	Mechanical	u	Combined	u	Trained	Ľ	Untrained	4	Short	u	Long	c
lmmedia IL10	itely post SMD (95% Cl)	0.72 (0.01, 1.4)	-	0.42 (-0.40, 1.24)	-	0.76 (-0.18, 1.71)	m	0.82 (-0.4. 2.1)	4	0.76 (-0.2, 1.7)	-	0.01 (-0.4, 0.4)	m	2.15 (-0.8, 5.1)	2
TAC	SMD (95% CI)	1.07 (0.4, 1.8)	4	0.10 (-0.4, 0.6)	2	92.7 0.13 (-0.6, 0.9)	2	0.56 (0.1, 1.0)	8	P/N		0.28 (-0.1, 0.6)	5	1.23 (0.2, 2.3)	ŝ
MVC	r SMD (95% CI) 2	60.0		0.0 0.47 (0.1, 0.9)	4	36.6 0.41 (-0.1, 0.9)	m	61./ 0.31 (-0.1, 0.7)	5	0.78 (0.2, 1.3)	2	20.0 0.45 (0.1, 0.8)	7	5.17	
GPX	SMD (95% CI)	-0.40 (-1.3, 0.5)	4	0.04 (-0.8, 0.9)	-	0.0		-0.37 (-1.2, 0.5)	4	0.00 (-1.1, 1.1)	-	0.04 (-0.8, 0.9)	-	-0.40 $(-1.3, 0.5)$	4
SOD	SMD (95% CI)	-0.63 (-1.2, -0.1)	с С	-0.13 (-0.7, 0.44)	2	-0.54 (-1.4 , 0.3)	-	-0.42 (-0.8, -0.1)	9	N/A		-0.26(-0.7, 0.2)	ĸ	$-0.63 \left(-1.2, -0.1 \right)$	с
DOMS	r SMD (95% CI) 2	0.0		0.0 -0.04 (-1.2, 1.1)	7	0.0 -0.31 (-0.8, 0.2)	7	0.0 -0.35 (-0.8, 0.1)	8	0.55 (-0.3, 1.4)	-	0.0 —0.25 (—0.7, 0.2)	6	0.0	
TBARS	ו ^ב SMD (95% CI) ני	-0.79 (-1.7, 0.1)	m	73.9 -0.14 (-0.6, 0.3)	4	62.2 0.12 (-0.7, 0.9)	7	56.5 -0.40 (-0.8, 0.00)	8	N/A 0.47 (-0.1, 1.0)	-	-0.51 (-1.3, 0.3)	5	-0.08 $(-0.5, 0.4)$	4
CRP	r SMD (95% CI)	02.0 -0.20 (-0.6, 0.2)	2	0.9 -0.25 (-0.7, 0.2)	4	00.4 -0.26 (-0.5, -0.02)	5	-0.24 (-0.4, -0.1)	6	–0.24 (–0.7, 0.2)	2		6	0.0 -0.23 (-0.7, 0.2)	2
TNFα	ا ^ر SMD (95% CI)	0.0 0.38 (0.8, 0.1)	4	0.0 -0.45 (-1.3, 0.4)	-	0.0 -0.48 (-1.4, 0.5)	2	0.0 0.34 (0.7, 0.03)	9	0.0 -0.60 (-1.3, 0.1)	-	0.0 —0.29 (—0.7, 0.1)	ŝ	0.0 -0.59 (-1.1, -0.04)	2
IL−6	ا ^ر SMD (95% CI)	0.0 - 0.88 (-1.4, -0.4)	4	N/A -0.05 (-0.9, 0.8)	-	53.5 0.03 (—0.9, 1.0)	9	0.0 -0.19 (-0.8, 0.4)	10	N/A -1.24 (-2.0, -0.5)	-	0.0 —0.44 (—2.0, 0.1)	∞	0.0 0.20 (-1.7, 2.1)	m
£	ا ^ر SMD (95% CI)	6.6 -0.16 (-0.6, 0.3)	9	N/A 0.25 (-1.0, 1.5)	2	85.5 —0.12 (—0.4, 0.2)	9	77.6 -0.01 (-0.3, 0.3)	12	N/A -0.70 (-1.7, 0.3)	2	61.9 -0.00 (-0.3, 0.3)	12	92.8 - 0.83 (-1.6, -0.04)	2
24h nost	. 13	38.2		78.1		0.7		22.2		52.4		19.3		11.7	
TAC	SMD (95% CI)	1.51 (-0.4, 3.5)	ŝ	0.56 (-1.3, 2.4)	7	0.16 (-0.6, 0.9) 38.6	2	0.68 (-0.2, 1.6) 0.3 0	9	1.55 (0.5, 2.6) N/A	-	$-0.04 \ (-0.6, \ 0.5)$	ĸ	1.5 (0.1, 2.9) 85.0	ŝ
CMJ	SMD (95% CI)	7.00		0.000		0.62 (0.01, 1.2)	9	0.62 (0.01, 1.2)	9			0.62 (0.01, 1.2)	9	0.00	
MVC	SMD (95% CI) 212	0.97 (-0.1, 2.0)	-	0.22 (-0.2, 0.6)	6	0.99 (0.6, 1.4)	5	0.58 (0.1, 1.1)	6	0.43 (0.02, 0.9) 55 3	9	0.55 (0.2, 0.9)	13	0.30 (-0.1, 0.7)	2
SOD	SMD (95% CI)	-0.42 (-1.0, 0.1)	4	0.10		-0.60(-1.4, 0.2)	-	-0.46 (-0.9, -0.03)	2	C.CC		-0.60(-1.4, 0.2)	-	-0.42 (-1.0, 0.1)	4
DOMS	SMD (95% CI)	-0.25 (-1.0, 0.4)	2	-0.14 (0.4, 0.1)	8	-0.33 (-0.6, -0.08)	10	-0.33 (-0.5, -0.1)	13	-0.09 (-0.4, 0.2)	7	-0.25 (-0.4, -0.07)	18	-0.14 (-0.5, 0.3)	2
TBARS	SMD (95% CI)	-0.46(-1.3, 0.3)	S	0.27 (-0.3, 0.9)	7	0.0		-0.41 (-1.0, 0.2)	9	2.1 0.55 (-0.03, 1.1)	-	0.0 0.41 (_0.00, 0.9)	ĸ	0.0 -0.74 (-1.5, -0.02)	4
CRP	r SMD (95% CI)	83.5 —0.26 (—0.7, 0.2)	m	0.0 —0.17 (—0.8, 0.5)	-	-0.19 (-0.9, 0.5)	Ŋ	/3.9 -0.16 (-0.6, 0.3)	8	N/A —0.35 (—0.9, 0.2)	-	0.0 —0.22 (—0.6, 0.2)	7	69.9 -0.03 (-0.8, 0.7)	2
TNFα	ا ^د SMD (95% CI)	0.0 —0.34 (—0.9, 0.2)	ŝ	N/A -2.2 (-3.4, -1)	-	67.6 0.12 (—0.7, 0.9)	-	46.8 —0.19 (—0.6, 0.3)	4	N/A -2.2 (-3.4, -1)	-	49.9 0.10 (-0.5, 0.7)	7	25.3 -1.03 (-2.0, -0.01)	m
IL-6	ا ^ح SMD (95% CI)	0.0 0.15 (-0.3, 0.7)	m	N/A -1.25 (-3.1, 0.6)	7	N/A -0.41 (-1.2, 0.4)	4	0.0 -0.17 (-0.6, 0.3)	∞	N/A -2.26 (-3.4, -1.1)	-	-0.04 (-0.5, 0.4)	9	67.9 -1.18 (-2.5, 0.1)	ĸ
ť	r SMD (95% Cl) 1 ²	19.0 -0.17 (-0.5, 0.2) 0.0	9	86.0 0.38 (-0.4, 1.1) 48.0	2	63.3 -0.32 (-0.7, 0.1) 0.0	5	48.4 —0.09 (—0.3, 0.2) 0.0	12	N/A -0.42 (-1.1, 0.3) N/A		40.9 0.11 (0.4, 0.2) 8.4	6	/8.6 —0.18 (—0.6, 0.3) 0.0	4
48h post	t 				0		6								Ċ
TAC	SMD (95% CI) ²	0.35 (—0.4, 1.1) N/A	-	-0.04(-0.5, 0.5)	7	0.78 (0.03, 1.5) 56.9	m	0.40 (—0.04, 0.9) 79.4	9			0.15 (—0.2, 0.5) 0.0	-	0.94 (—0.3, 2.2) 76.1	7
CMJ	SMD (95% CI) 1 ²					0.57 (0.04, 1.1)	9	0.57 (0.04, 1.1) 63 9	9			0.71 (0.1, 1.3) 63.5	9	-0.20 (-1.0, 0.6) N/A	-
MVC	SMD (95% CI)	1.26 (0.2, 2.4)	-	0.39 (-0.00, 0.8)	6	1.19 (0.6, 1.8)	5	0.83 (0.4, 1.2)	6	0.44 (-0.2, 1.0)	9	0.78 (0.4, 1.2)	13	0.12 (-0.3, 0.5)	2
														(cont	tinued)

Table 2. Subgroup analysis on moderator variables for effect of ACN on recovery.

								Subg	Iroup						
				Exercise type				Training	g stat	tus		Study	y dur	ation	
Variable		Metabolic	и	Mechanical	и	Combined	ч	Trained	и	Untrained	и	Short	u	Long	u
	-1	N/A		63.4		53.1		50.1		76.7		65.5		0.0	
DOMS	SMD (95% CI) ²	-0.28 (-1.0, 0.4) 0.0	7	018 (0.6, 0.2) 55.8	8	-0.20 (-0.5, 0.1) 19.2	10	-0.18 (-0.4 , 0.1) 10.6	13	-0.19 (-0.6, 0.2) 55.9	7	-0.20 (-0.4, 0.03) 34.3	18	-0.20 (-0.7, 0.3) 16.2	2
CRP	SMD (95% CI) 12	-0.10 (-0.8, 0.6)	m	-0.30 (-0.8, 0.2)	2	-0.32 (-0.9, 0.3)	S	-0.22 (-0.6, 0.2)	6	-0.42 (-1.0, 0.2)	-	-0.30 (-0.7, 0.1)	∞	-0.09 (-0.8, 0.6)	2
TNFα	SMD (95% CI)	-0.08 (-0.8, 0.6)	7	-0.49 (-1.3 , 0.3)	-	-0.38 (-1.1, 0.4)	7	-0.29(-0.7, 0.1)	9			-0.29 (-0.7, 0.1)			
IL6	SMD (95% CI) I ²	-0.70 (-1.3, -0.1)	с С	-0.16 (-0.6, 0.3)	2	-0.21 (-0.9, 0.5)	4	-0.28 (-0.7, 0.1) 44 7	8	-0.58 (-1.6, 0.4) N/A	-	-0.30 (-0.7, 0.1) 39 3	6		
ť	SMD (95% CI) ²	-0.33 (-1.3, 0.6) 60.1	m	-0.24 (-0.7, 0.3) 41.8	4	-0.36 (-0.7, -0.06) 0.0	7	-0.27 (-0.5, -0.01) 17.4	12	-0.60 (-1.2, -0.0) 0.0	2	-0.29 (-0.5, -0.04) 16.8	13	-0.58 (-1.4, 0.2) N/A	-
Subgrou (MVC);	p analysis for: co superoxide dism	untermovement jum utase (SOD); thiobark	p (CN bituric	AJ); C-reactive proteir c acid reactive substa	n (CRF ances	P); creatine kinase (CK); (TBARS): total antioxid;	: dela) ant ca	ved onset of muscle dar apacity/status (TAC) and	age tumo	(DOMS); glutathione or necrosis factor alof	perox (TN	(idase (GPx); interleukin $JF\alpha$). Grav cells indicate	(IL-)	maximal voluntary continution $u = n$	raction

Table 2. Continued

dietary restrictions (Table 1) to reduce phenolic intake. This might lead to an overestimate in the effect, as removal of natural antioxidants from the diet might conceptually impair the natural recovery process; therefore ACN might only restore antioxidant capacity whereas the placebo remains in a depleted state. The balance between reducing background noise and ecological validity needs careful consideration in research designs (Bowtell and Kelly 2019). Thirdly, there was a large difference between ACN content of the interventions and it is not possible to distinguish between different types of ACN, which could have different bioactivities (Rechner and Kroner 2005). Notwithstanding, ACN content is often reported as cyanidin equivalents (Bell et al. 2016; Brown, Stevenson, and Howatson 2019; Hutchison et al. 2016; O'Connor et al. 2013) and this compound is an established biomarker of berries (Sandoval-Ramírez et al. 2020) and tart cherries (Seymour et al. 2014) suggesting at least some commonality between the interventions. Moreover, this is the first review to comprehensively study ACN on exercise recovery, including a meta-regression of ACN dose. Nonetheless, future studies should try to distinguish the optimum type and dosage of anthocyanins for recovery, an important factor highlighted in a recent review (Sabou et al. 2021). Lastly, blinding of studies was a major source of bias, although it is acknowledged that this is an inherent challenge with studies involving functional foods (Brown et al. 2018). Therefore, results from this meta-analysis have to be interpreted in light of limitations of the literature highlighted above. Nonetheless, the meta-analytical technique is currently the best method to systematically consolidate evidence from previous work (Haidich 2010), but it should be conducted with a forensic eye of the literature in order to interpret the information with insight.

To summarize, ACN were shown to have an overall beneficial effect on reducing CK, muscle soreness, strength loss and improving power after exercise. This was accompanied by attenuated inflammation and increased antioxidant capacity/status following the intake of ACN, suggesting a potential causal link. The information provided by subgroup analyses suggested the most beneficial effect on the biomarkers are following metabolically biased exercise and longer-term interventions; whereas shorter duration interventions saw most benefit on physiological variables, which can collectively help inform research designs and application of ACN in exercise recovery. These data provide new information to support the use of ACN-rich foods in promoting recovery following strenuous exercise that can inform exercisers and practitioners.

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