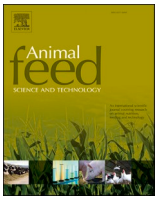
Animal Feed Science and Technology 344 (2026) 116898

Contents lists available at ScienceDirect

Animal Feed Science and Technology

journal homepage: www.elsevier.com/locate/anifeedsci



Research article

A CORKING GOOD FEED: How "Floating Faeces" improve solid and nutrient removal in Atlantic salmon RAS

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ARTICLE INFO

Keywords:
Cork
Floating faeces
Functional aquafeeds
Particle-bound nutrients
Salmonids
Solid management

ABSTRACT

Particle accumulation continues to be one of the biggest challenges to successful recirculating aquaculture systems (RAS), compromising system stability, fish physiology and welfare, and occasionally even leading to operational failure. This study tested the feasibility of dietary cork as a functional feed ingredient to reduce faecal density, promote faecal flotation, and thus facilitate swift and efficient removal of solids and nutrients from production systems husbanding the freshwater phase of Atlantic salmon. A 21-week experiment was conducted comparing a functional feed including 3% cork with a commercial reference diet without cork. The inclusion of cork in the diet resulted in the majority of faecal casts having densities lower than that of water (< 1.00 g cm^{-3}). As a result, the faeces floated on the surface from where they could be easily captured, resulting in an 87% drum filter removal efficiency—more than twice that of the control diet. Nutrient removal efficiency for both total phosphorus (90%) and nitrogen (70%) was also distinctly higher in RAS supplied with the cork diet. Despite a slight reduction in intrinsic dry matter digestibility, the cork diet did not negatively impact fish survival or feed conversion; indeed, fish in the experimental system exhibited improved growth. The collection of floating faeces required only a simple modification of surface skimming equipment, with no negative effects on fish or overall system functionality. This approach can thus be applied to existing RAS to promote more efficient solid and nutrient removal and improved performance.

1. Introduction

The ongoing global environmental crisis is fundamentally reshaping the way aquaculture is practised, driving technological innovations to foster sustainability while rising to the challenges of food security and supply worldwide (Costello et al., 2020). Among these forward-looking innovations, recirculating aquaculture systems (RAS) have received significant attention (Ahmed and Turchini, 2021; Timmons et al., 2018), as they offer several environmental and logistical advantages, particularly in response to tightening legislation being imposed on traditional systems, *e.g.* within the European Union (Badiola et al., 2012; Heiderscheidt et al., 2020; Martins et al., 2010). The ability of RAS to recycle and reuse water (Timmons et al., 2018) and retain effluent emissions allows for end-of-pipe treatment (Flo et al., 2024), optimising resource efficiency (Martins et al., 2010) and opening recycling opportunities for production-derived waste (Ende et al., 2024). Further opportunities for more efficient and versatile land use (Badiola et al., 2018) and close control of production cycles (Martins et al., 2010) position RAS as a highly competitive alternative to traditional methods

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https://doi.org/10.1016/j.anifeedsci.2026.116898
Received 7 October 2025; Received in revised form 4 June 2026; Accepted 11 June 2026
Available online 19 June 2026

(EUMOFA, 2020; Timmons et al., 2018).

However, despite these intrinsic advantages, RAS-based fish production remains somewhat ancillary in the sector. This is mainly due to its high economic and energy costs, coupled with concerns regarding water quality, which is of paramount importance to both animal welfare (Frisk et al., 2020; van de Vis et al., 2020) and system integrity (Becke et al., 2017; Fudge et al., 2023; van Rijn, 2012). Failures in pilot and commercial RAS, and the associated costs, as reported in niche media (Cherry and Mutter, 2019), are often attributed to less effective management or design, resulting in water quality issues. In some cases, off-flavours in produce have led to reductions in marketability (Negrete, 2024). In other instances, mass mortalities have occurred as a result of lethal compounds, such as hydrogen sulphide (H_2S) (Letelier-Gordo et al., 2020) forming in system compartments, including production tanks (Fishfarmingexpert, 2021; Nygård et al., 2022; Undercurrent News, 2023; White, 2021). The complexity of RAS operations has been identified as a factor contributing to certain operational failures, raising questions over their economic viability (Badiola et al., 2012; Bjørndal and Tusvik, 2019; Lasner et al., 2016) and fuelling criticism of high-density aquaculture operations on animal welfare grounds. Yet, the central cause of these issues in RAS is singular: the accumulation of particulate matter, which triggers the degradation of the system's aquatic environment and impairs its overall performance (Timmons et al., 2018).

All aquaculture operations generate suspended solids (SS), and their accumulation is naturally greatest in systems reusing water. These system-derived particles consist predominantly of fish faecal matter, while uneaten feed and microbial aggregates make up a smaller but still relevant fraction (Li et al., 2023; Schumann and Brinker, 2020). Faecal production is largely determined by the quantity of feed provided and its digestibility (Schumann and Brinker, 2020). This issue is an old and persistent one, not specific to RAS (Brown et al., 2024; Gupta et al., 2024; Slette et al., 2024), that has long affected aquaculture's reputation as a long-term contributor to eutrophication and the degradation of effluent areas (Brinker and Rösch, 2004; Brinker et al., 2005; Schindler et al., 2016). While RAS offers the potential for tight control over environmental discharge, the continuous recirculation of water generates substantial turbulence and shear forces that accelerate the fragmentation of particulate matter (McMillan et al., 2002; Schumann and Brinker, 2020), making SS management a key challenge. Particle breakdown considerably reduces the efficacy of mechanical filtration and SS removal, leading to a progressive accumulation of fine and more soluble suspended materials, as well as the leaching of particulate-bound nutrients—phosphorus (P) and nitrogen (N) (Ruiz et al., 2019; Stewart et al., 2006; Heiderscheidt et al., 2020). Elevated loads of fine solids in RAS pose significant challenges to both system performance and fish health (Schumann and Brinker, 2020). The accumulation of organic matter can unbalance the natural microbial community of a system by reducing biofilter capacity through clogging and the consequent reduction of the area available for bio-nitrifiers to grow (Fernandes et al., 2025; Michaud et al., 2013; Timmons et al., 2018). It also favours the proliferation of heterotrophic bacteria, which directly compete with essential nitrifiers inside the biofilter (Michaud et al., 2013; Rojas-Tirado et al., 2018). As a result, both biological oxygen demand (BOD) and carbon dioxide (CO_2) production increase (Timmons et al., 2018), pipe clogging becomes more frequent (de Jesus Gregersen et al., 2024) and the formation of toxic compounds is promoted (Becke et al., 2018; Li et al., 2023). Additionally, fine SS can hamper sterilisation devices, for example, by attenuating ultraviolet (UV) light penetration. Suspended particles may act as a shield, protecting microorganisms embedded within them from UV exposure, thus allowing some pathogens to survive treatment (Farrell et al., 2017; Pedersen et al., 2017; Sharrer et al., 2005).

Over the years, several approaches have been studied to lessen the accumulation of SS in intensive RAS. The vast majority of such particles are < 30 μm (Becke et al., 2018; Cripps and Bergheim, 2000; Patterson et al., 1999), and methods deployed to remove them include microscreening (Timmons et al., 2018), foam fractionation (de Jesus Gregersen et al., 2021; Kovács et al., 2023), and ozonation (de Jesus Gregersen et al., 2021), among others. Despite their various advantages, these methodologies all entail significant investment and operational costs, and merely extend the time before system water must be changed (Li et al., 2023; Xiao et al., 2018). There is, thus, an urgent need for novel approaches to secure early-stage mitigation, ideally within the confines of existing systems (Schumann et al., 2016; Unger et al., 2015).

This study is based on the "floating faeces" concept (Unger and Brinker, 2013) and investigates the quantitative effects of dietary cork (*Quercus suber* L.) as a functional ingredient to reduce faecal density and promote early solids removal from a full-RAS operation husbanding the freshwater phase of Atlantic salmon (*Salmo salar* L.). To this end, 3% cork granules were added to a commercially available RAS feed in order to generate buoyant faecal casts. Additionally, a simple tank upgrade in the form of a surface skimmer was deployed, enabling the direct removal of floating faeces from a minimal fraction of total water flow. We hypothesised that the inclusion of cork would significantly improve solid and nutrient removal efficiency by enhancing faecal buoyancy, thereby allowing their rapid removal via surface skimming, while maintaining or even improving fish performance through better overall water quality resulting from reduced suspended solids.

2. Materials and methods

The experiment was conducted from February to July 2023 at the Fisheries Research Station of Baden-Württemberg (Langenargen, Germany), strictly following German (TierSchG) and European (Directive 2010/63/EU) guidelines on the protection and welfare of animals used for scientific purposes.

2.1. Experimental diets

A commercial standard RAS feed (BioMar Group, Aarhus, Denmark) designed for the freshwater phase of Atlantic salmon formed the basis of both diets in this study. This base feed was used to prepare a Control diet with the addition of 0.3% guar gum (GG) and 0.05% yttrium oxide (Y_2O_3), and a test diet (+Cork) with the exact same base formulation and additives, plus an additional inclusion of

3% indigestible cork granules (size range: 0.7–1 mm). GG, a well-established binder, *e.g.* in RAS commercial feeds, was included in both diets. At this inclusion level, GG significantly alters faecal rheological properties, increasing their elastic modulus and viscosity, thereby improving faecal integrity, particle size, and solids removal efficiency (Brinker, 2007; Brinker and Friedrich, 2012). In the cork-based diet, the binder additionally ensured that small cork particles were securely retained within the faecal matrix, thereby providing maximal buoyancy. Y_2O_3 served as an inert marker for digestibility measurements. The +Cork diet was prepared according to Unger et al. (2015), ensuring cork granule integrity during extrusion, ingestion, digestion and excretion. Feeds were kept in an aerated cooling chamber at 5 °C to preserve their properties. All the manufacturing details are property of BioMar Group, but available information regarding formulation is presented in Table 1.

2.2. Experimental operation and set-up

A pool of Atlantic salmon fingerlings obtained from Danish Salmon A/S (Hirtshals, Denmark) was acclimatised to the commercial Control diet for three months, then divided as pre-smolts into two balanced groups (initial body weight: 74.8 ± 11.4 g) and allocated randomly into two replicate semi-technical RAS at initial stocking densities of 20.2 kg m^{-3} (+Cork) and 20.6 kg m^{-3} (Control). The operational conditions of both systems throughout the experiment are summarised in Table 2. Each RAS comprised a total volume of 6 m^3 held in 10 green circular fibreglass tanks (volume: 0.33 m^3), a moving-bed bioreactor (MBBR; volume: 1.6 m^3; active surface: 355 m^2; max. removal capacity: ≈ 3 kg feed day^{-1}) with honeycomb-shaped elements (K 3, 500 m^2 m^{-3} protected surface area, AnoxKaldnes, Sweden), a drum filter (mesh size: 100 μm; HDF 801 1 H, Hydrotech, Sweden), and a UV disinfection system (Berrier L20, Wallace & Tiernan, Günzburg, Germany) (see Supplementary Material S1). The systems were operated in full-RAS mode (daily water exchange: ≈ 3%), made up using sand-filtered water taken from a depth of 30 m in Lake Constance. The photoperiod was fixed at 12 L:12D, *i.e.*, 12 h light and 12 h darkness (Lumilux® daylight lamps provided ≈ 160 lux at the water surface) between 07:30 and 19:30, with a 30-min sigmoidal light transition designed to simulate dawn and dusk.

The systems were each assigned to one of the dietary treatments (Control and +Cork). To control for possible system effects, the

Table 1
Formulation of the experimental diets.

Diets	Control	+Cork
		
Ingredients, % DM		
Fish meal[a]	40.00	40.00
Soy protein concentrate[b]	17.20	17.20
Wheat gluten[c]	2.86	2.86
Vegetable raw materials	17.73	17.73
Vegetable oil[d]	7.79	7.79
Fish oil[e]	13.10	13.10
Vitamin and mineral premixes	0.464	0.464
Yttrium oxide[f]	0.05	0.05
Other (incl. pigment)	0.502	0.502
Guar gum[g]	0.30	0.30
Cork[h]	-	3.00
Total	100.00	103.00
Proximate composition, %		
Moisture	5.9	6.4
Crude Protein	44.90	44.01
Crude Fat	25.0	25.9

Dietary composition is described using values estimated from near-infrared spectroscopy (NIRS) for moisture and fat content, and by a combustion-based method (DUMAS) for crude protein, due to out-of-target NIRS results for the +Cork diet. Both diets were extruded into 4.5 mm pellets. The Control diet reached a maximum extrusion pressure of 44 bar (average 18 bar), while the +Cork diet reached a maximum of 30 bar (average 4 bar). Ingredient sources:

[a] Eskja, Iceland; Köster, Peru;
[b] Köster, Brazil;
[c] BaneoPro, Belgium;
[d] Scanola, Sweden/Denmark;
[e] Venta FM, Latvia;
[f] Rare Earth metals, China;
[g] Seah, France/India;
[h] Amorim, Portugal; size range: 0.7–1.0 mm.

Table 2
Operational conditions of RAS units under study.

Parameters	Control	+Cork
Tank shape	Circular	Circular
Photoperiod	12 L:12D	12 L:12D
Number of tank units	10	10
Tank volume (m^3)	0.33	0.33
RAS volume (m^3)	6.00	6.00
System daily water exchange (% of RAS vol.)	3.26	3.10
Tank water velocity (cm s^{-1})	11.67	12.33
Swim velocity (BL s^{-1})	0.47	0.51
Tank flow rate (m^3 h^{-1})	0.394	0.391
Tank HRT (min.)	50.38	50.65
System feed rate (kg day^{-1})	2.09	2.05
Feed load/water exchange (kg m^{-3} day^{-1})	11.42	10.71
Feed load (% of MBBR capacity)	69.74	68.42
Estimated removal via overflow (%)	4.27	60.27

Values are presented as means of each treatment over the entire experimental period. RAS: recirculating aquaculture system; HRT: hydraulic retention time; BL: body length; MBBR: moving-bed bioreactor.

experimental diets were switched between systems after 12 weeks, sectioning the experiment into two phases (Phase I and Phase II). Fish were hand-fed three times a day (08:30, 12:30 and 16:30), seven days per week (Sunday to Saturday), to apparent satiation, thus minimising excess feed. The quantity of feed allocated to each tank was recorded daily.

To manage solids, all tanks were equipped with a central bottom drain for the collection of settling solids, which were purged twice daily (after morning and afternoon feeding) into the mechanical drum filter. In addition to the central drains, each tank featured a sidewall drain for continuous removal of suspended residues. In tanks receiving the +Cork diet, an overflow stainless-steel slot-cut pipe was installed to facilitate effective removal of buoyant faeces from the water surface to the drum filter (Fig. 1; Supplementary Material S2).

2.3. Biological samples collection

At the beginning, on treatment-switching day, and at the end of the experiment, all fish were individually weighed (g), measured

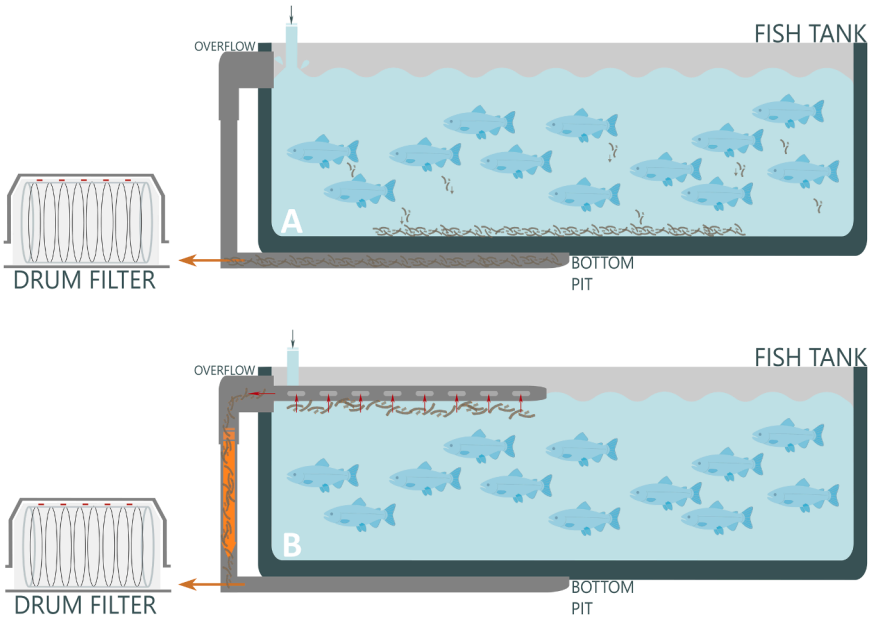

Fig. 1. Schematic representation of the two solid removal principles tested in this study: (A) Control treatment – utilises sedimentation, a traditional method in commercial aquaculture. Solids settle at a central bottom pit and are drained twice daily to a drum filter. (B) +Cork treatment – removal via overflow takes place by integrating stainless-steel slot-cut pipes connected to an overflow skimmer box at the water surface. This removes floating waste, bypassing the bottom pit. Any remaining solids undergo sedimentation as in A. The mechanism of floating faeces removal in the +Cork treatment is demonstrated in Supplementary Material S2 (video).

(cm), and examined for external macroscopic abnormalities. At the end of the experiment, a pool of eight fish from each tank was euthanised by stunning with a sharp blow to the head, followed by a sacrificial gill cut, prior to distal intestinal dissection and collection of faecal material for digestibility and density measurements (de Sousa e Brito et al., 2025; Sanden et al., 2005). The same procedure was performed on the switching day; however, due to an insufficient number of faecal casts found in the intestinal tracts, samples had to be pooled from five tanks instead of analysing each tank individually. Immediately after euthanasia, the livers and intestines were resected and inspected for macropathological disorders (*e.g.* general structural integrity, changes in colouration, anaemia, necrosis, passive/active hyperaemia, and haemorrhage).

2.4. Apparent dry matter digestibility and faecal density

The previously dissected faecal material was lyophilised and homogenised as described by Schumann et al. (2016). Approximately 100 mg of faecal material from each sample was then transferred into pressure digestion vessels and processed in a microwave pressure digestion system (SPEEDWAVE Four, Berghof Eningen, Germany). For digestion, a reagent solution prepared by combining 2 mL of nitric acid (HNO_3; 65%), 1 mL of hydrogen peroxide (H_2O_2; 30%, stab. p.a.), and 5 mL of distilled water was added to the vessels. Dry matter (DM) content was determined as the ratio of dry to wet weight before and after lyophilisation. Y_2O_3 levels were quantified using inductively coupled plasma mass spectrometry (ICP-MS), performed at the federal chemical analysis service of Baden-Württemberg (Sigmaringen, Germany).

The apparent digestibility coefficient of dry matter (ADC_{DM}) was calculated as follows:

$$ADC\ (\%,\ DM) = 100 \times (1 - (Y_2O_3\ _{(feed)} / Y_2O_3\ _{(faeces)}))$$

Faecal densities were determined by exposing the dissected faeces to a Y-oscillation density meter (DMA 3, Anton Paar GmbH, Austria). Measurements were taken at two intervals, according to Unger and Brinker (2013): directly after dissection and after one hour of soaking in distilled water, in order to simulate and perceive the effects of water absorption.

2.5. Faecal removal via overflow

Faecal removal efficiency in the +Cork and Control systems was assessed through 24-hour measurements conducted at least once per week using specialised equipment designed and built with the objective of retaining all floating material larger than 400 μm released via the tank overflow pipes, without interfering with system water circulation (see Supplementary Material S3). Every two or four hours, the retained content was collected and dried, and dry-to-wet weight ratios were calculated.

To obtain a more realistic value for faecal matter being removed from the tank surface, a further conservative estimate of ADC was made by removing the cork dilution factor from the +Cork diet as follows:

$$ADC_{corrected}\ (\%,\ DM) = 100 \times (1 - ((Y_2O_3\ _{(feed,\ +Cork)} / Y_2O_3\ _{(faeces,\ +Cork)}) \times (DM\ _{faeces,\ +Cork} / DM\ _{feed,\ +Cork})) / (Y_2O_3\ _{(faces,\ +Cork)} / Y_2O_3\ _{(feed,\ +Cork)})$$

Estimates for removal via overflow (RO) were calculated as ratios of DM removal to predicted faecal excretion, based on feed intake data from the three days preceding the measurement. This three-day period took into account the likely effects of water temperature, as well as the coarseness and reduced digestibility of the +Cork diet, on the speed of gastric emptying (Aas et al., 2021; Handeland et al., 2008; Sveier et al., 1999).

$$RO\ (\%) = 100 \times (DM\ removed\ via\ overflow / predicted\ faecal\ DM\ excretion)$$

2.6. Total suspended solids (TSS) sample collection and measurements

Water samples were collected weekly, before morning tank drainage to reflect the standard system operating conditions, from three system locations: before the drum filter (BDF), after the drum filter (ADF) and from the backwash water (BWW; each measurement representing a single backwash interval). Samples were taken in duplicate and used to determine TSS via positive-pressure filtration using compressed air through a cellulose acetate membrane filter (⌀ 50 mm, 1106–50 N, Sartorius AG, Göttingen, Germany; pore size 0.45 μm). Sample volumes ranged from 50 to 1000 mL, depending on the solid load at each sampling point. Prior to filtration, all filters were oven-dried at ≈ 103 °C for one hour or until a constant weight was achieved and finally weighed to the nearest 0.1 mg. After filtration, the same drying and weighing procedure was repeated to assess the mass of TSS at each sampling point and obtain values for mechanical removal efficiency.

Removal efficiency (RE) during system operation was calculated as follows:

$$RE\ (\%) = 100 \times ([sample]_{after} / [sample]_{before})$$

2.7. Particle-bound nutrient measurements and leaching potential

The particle filtrate resulting from the above process was collected and immediately analysed to determine concentrations of total phosphorus (TP) and total bound nitrogen (TN_b) in the filtrate fraction using LCK cuvette tests with appropriate measuring ranges

(Hach-Lange, Germany). The filters were frozen and stored at −20 ºC until required for further processing as follows.

Filters were transferred individually to pressure digestion vessels and processed in a microwave pressure digestion system (SPEEDWAVE Four, Berghof, Eningen, Germany). To accomplish a successful filter digestion, an initial digestion reagent solution was prepared by combining 5 mL of hydrogen peroxide (H_2O_2; 30%, stab. p.a.), 2 mL of distilled water and 1 mL of sulphuric acid (H_2SO_4), and rested for at least 15 min. An additional 2 mL of distilled water was subsequently added to the solution for the ADF and BDF sampling points before filters and solutions were transferred to the microwave system. The digestion cycle conditions for ADF and BDF samples were programmed as follows: an initial T^a of 110 °C (reaching the boiling point of H_2O_2 (≈ 108 °C)) and a pressure of 25 bar, with a ramp rate of 2 °C min^{-1}, holding for 5 min at a power of 50 W. The system was then heated to 180 °C at 30 bar, with a ramp rate of 8 °C min^{-1}, held for 25 min at 90 W. The T^a was then increased to 200 °C, maintaining a pressure of 30 bar, with a ramp rate of 1 °C min^{-1} for 25 min at 90 W. Afterwards, the system was cooled to 50 °C at 25 bar, with a ramp rate of 1 °C min^{-1}, held for 5 min at 25 W. Finally, the system was held at 50 °C and 10 bar, with no ramp and no power input to allow for safe depressurisation before the samples were removed for further analysis. The treatment for BWW samples differed slightly to account for higher particle concentrations, with the holding times at steps 1 and 4 being extended from 5 to 10 min to ensure complete digestion. After cooling, the samples were transferred to 100 mL flasks and calibrated with a 3% sodium metaborate tetrahydrate ($NaB_3O_3{\cdot}4H_2O$) solution, with controlled addition of sodium hydroxide (< 0.28 g) to adjust pH to the recommended range for accurate LCK cuvette test analysis. This process ensured interference-free quantification of particle-bound P and TN_b. Removal efficiencies of the different particle-bound nutrients were calculated according to the equation given in 2.6.

Leaching potential (LP), by which P and TN_b might escape from the particulate to the dissolved fraction and into the system water of the RAS, was assessed by comparing the nutrient concentrations of P and TN_b in the filtrate fraction to total nutrient concentrations (filtrate + filter) in each sample, using the following formula:

$$LP\ (\%) = 100 \times ([Filtrate]_{nutrient}/[Filtrate]_{nutrient} + [Filter]_{nutrient})$$

2.8. Water quality and chemistry

Values for ammonium-nitrogen (NH_4^+-N) (AMTAX SC, Hach-Lange, Germany), dissolved oxygen (DO), dissolved carbon dioxide (CO_2), and temperature (T^a) were obtained via continuous automated monitoring (Oxygen, CO_2 and T^a Probes, OxyGuard, Denmak). A further set of key water quality indicators, namely total ammonia nitrogen (TAN), nitrite nitrogen (NO_2^--N), nitrate nitrogen (NO_3^--N) and pH were analysed chemically three times per week (Monday, Wednesday, and Friday) at sampling points both before and after the biofilter. These measurements were determined by UV-Vis spectrophotometry (DR6000 UV–VIS Spectrophotometer with RFID Technology, Hach-Lange, Germany) in order to maintain water quality standards within established limits for Atlantic salmon (Timmons et al., 2018). Sodium bicarbonate ($NaHCO_3$) was periodically added to the pump sump as a buffer to maintain alkalinity within acceptable limits. Biofilter performance was monitored and calculated using the equation given in 2.6.

2.9. Other analytical determinations

The collected data were used to determine values for weight gain (WG), total feed intake (TFI), feed conversion ratio (FCR), specific growth rate (SGR), thermal-unit growth coefficient (TGC), protein efficiency ratio (PER) and feed load as a percentage of the moving-bed bioreactors' capacity (% of MBBR capacity), using the following equations:

$$WG\ \ (kg) = \sum_{i=1}^{n} (w_{final,\ i} - w_{initial,\ i})$$

$$TFI\ (kg) = \sum_{i=1}^{n} daily\ feed_{intake,i}$$

$$FCR = TFI/WG$$

$$SGR\ \ (\%/day) = 100 \times ((\ln\ W_{final} - \ln\ W_{initial})/\Delta t))$$

$$TGC = (W_{final}^{1/3} - W_{initial}^{1/3}) \Big/ (\sum T(^{\circ}C) \times \Delta t)$$

$$PER = WG/Protein\ intake$$

$$Feed\ load\ (\%\ \ of\ MBBR\ capacity) = 100 \times (Feed\ load\ \ (kg\ day^{-1})/MBBR\ capacity\ \ (kg\ day^{-1}))$$

2.10. Data analysis

The dataset was analysed using suitable linear models and one-way ANOVA, after initial inspections for normality and homogeneity of variance. A linear mixed model fitted with restricted maximum likelihood (REML) was applied to assess treatment effects on

growth performance, incorporating treatment, final body weight (W_f) and their interaction as fixed effects, and system variability as a random factor. The same modelling approach was used to analyse total suspended solids (TSS), nutrient concentrations, drum filter removal efficiency, faecal densities, and water quality parameters, adjusting for relevant fixed effects such as treatment, system biomass, and sample type while accounting for system and tank as random effects. To account for temporal autocorrelation resulting from repeated measurements over time within the same experimental units, an appropriate residual covariance structure was employed. For digestibility and nutrient leaching potential, one-way ANOVA was conducted, followed by pairwise independent *t*-tests. Statistical significance was set at $p < 0.05$, and all analyses were performed using JMP® Pro, version 17.2.0 (SAS Institute Inc.).

3. Results

3.1. Fish performance, feed utilisation, and general observations

From day one of the experiment, systems fed with the +Cork diet produced a significant amount of floating faecal material. Significant quantities of floating faeces were aspirated by the surface pipes immediately after defecation and carried directly into the drum filter (see Supplementary Material S2). Hand-feeding in the +Cork systems was slightly adjusted to prevent feed pellets with larger cork surface areas from escaping through the surface pipes. No adverse effects on feeding behaviour were observed associated with the distinct hydrodynamics of the cork pellets, the presence of floating faeces, or the surface pipes. In line with previous research in rainbow trout (Schumann et al., 2016; Unger et al., 2015), cork granules were clearly discernible and embedded within the faecal matrix (see Supplementary Material S2 and S3). Despite the absence of a quantitative assessment of cork particle recovery, the frequent observations and the distinct floating behaviour of the faecal casts indicate that the cork particles remained functionally intact during gastrointestinal passage. As shown in Table 3, fish in both RAS exhibited consistent growth performance and feed utilisation, in line with the commercial standards for Atlantic salmon (Aas et al., 2021). The inclusion of cork in the diet did not influence fish growth. TFI showed a tendency to be slightly higher in the Control compared to the +Cork group, though the difference was not significant. Although the +Cork group exhibited a slightly better FCR than the Control group, the difference did not reach statistical significance. Clear increases in SGR, TGC and PER were observed in fish fed with the +Cork diet. Survival rates were high in both groups and were not affected by the inclusion of cork. Model analysis revealed that the W_f factor significantly affected both WG and TFI; however, no significant interaction effects between treatment and W_f were observed.

3.2. Apparent dry matter digestibility, faecal density and overflow faecal removal

The apparent digestibility coefficient of dry matter (ADC_{DM}) was notably affected by the inclusion of cork in the diet. As evident in Table 4, the +Cork diet presented a significantly lower digestibility than the Control, but when the cork factor was corrected in the analysis, no significant differences in ADC_{DM} remained.

Faecal density was significantly influenced by the dietary treatment, with faeces from the + Cork group exhibiting significantly lower density than those from the Control group (Fig. 2). This difference was highly significant ($F_{(1,95)} = 890.04$; $p < 0.001$) in both soaked (Control: 1.03 ± 0.003 g cm^{-3}; +Cork: 0.98 ± 0.003 g cm^{-3}) and non-soaked samples (Control: 1.05 ± 0.003 g cm^{-3}; +Cork: 0.99 ± 0.003 g cm^{-3}); however, soaking in distilled water for one hour led to a significant reduction in density compared to non-soaked faeces ($F_{(1,117)} = 78.36$; $p < 0.001$). No significant interaction effects were found between treatment and sample type.

The results for solid removal efficiency via overflow devices—without correcting for the cork content of faeces—indicate that the system treated with cork achieved a removal rate of 60.27% of total solid load, while only 4.27% of solids were removed from the Control RAS (Table 2).

3.3. Total suspended solids and drum filter removal efficiency

TSS concentration in water samples collected before mechanical treatment was significantly influenced by the presence of cork in

Table 3
Growth performance, feed utilisation and survival of Atlantic salmon fed the experimental diets.

Diets	WG (kg)	TFI (kg)	FCR	SGR (% day^{-1})	TGC	PER	Survival (%)
Control	6.44 ± 0.69	7.31 ± 0.30	1.15 ± 0.02	0.73 ± 0.07^a	0.88 ± 0.09^a	2.06 ± 0.05^a	99.70 ± 0.20
+Cork	6.45 ± 0.69	7.16 ± 0.30	1.12 ± 0.03	0.77 ± 0.07^b	0.91 ± 0.09^b	2.18 ± 0.05^b	99.93 ± 0.22
Model effects (*p*-value)							
Treatment	0.888	0.061	0.084	0.0007	0.016	0.002	0.151
W_f	0.0003	0.029	0.537	0.325	0.949	0.565	0.948
Treatment*W_f	0.796	0.826	0.915	0.653	0.640	0.915	0.916

Values are presented as LS Means ± SEM; n = 20. Superscript letters indicate significant differences among treatments ($p < 0.05$). Wf: Final body weight; Treatment*Wf: Interaction between treatment and final body weight; WG: Weight gain; TFI: Total feed intake; FCR: Feed conversion ratio; SGR: Specific growth rate; TGC: Thermal unit growth coefficient; PER: Protein efficiency ratio.

Table 4
Apparent dry matter digestibility of both experimental feeds with and without cork dilution effect correction.

Diets	ADC_{DM} (%) *original*	ADC_{DM} (%) *wihout the cork dilution effect*
Control	79.55 ± 1.74[a]	79.55 ± 1.74
+Cork	74.55 ± 2.78[b]	77.70 ± 2.75
p-value	0.0005	0.062

Values are presented as LS means ± SE, superscript letters indicate significant differences among treatments ($p < 0.05$). ADCDM: Apparent digestibility coefficient of dry matter.

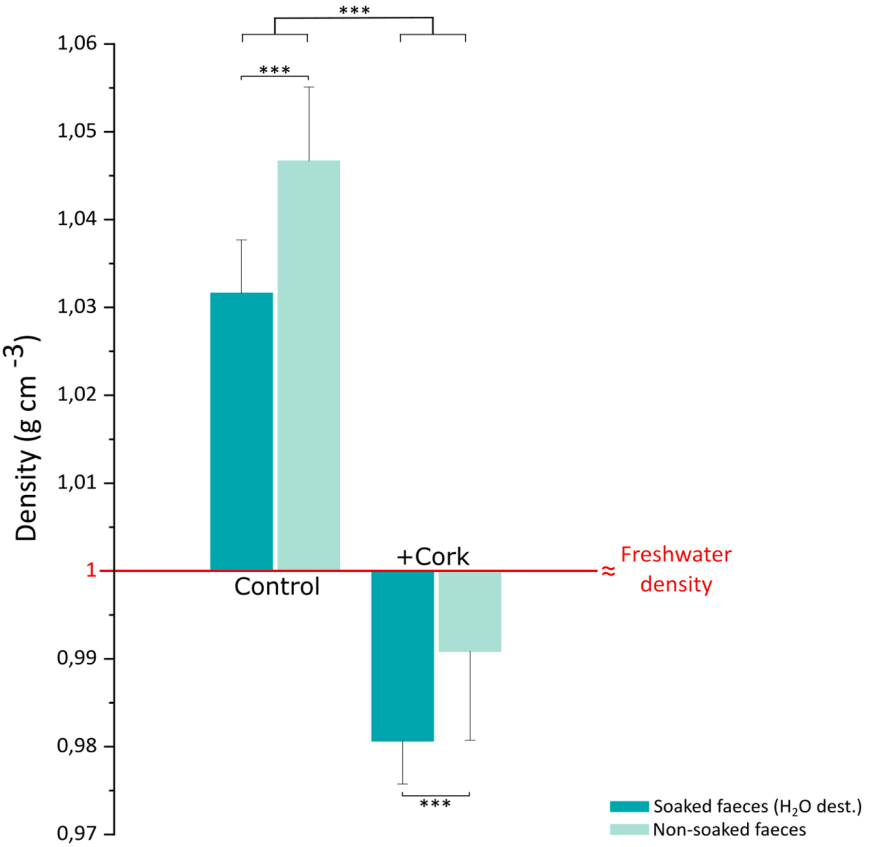

Fig. 2. Bar plot showing the densities of soaked and non-soaked faeces immersed in distilled water for one hour under Control and + Cork treatments. Bars represent the density relative to freshwater (approx. 1 g cm^{-3}), with values > 1 indicating higher density and values < 1 indicating lower density. Statistically significant differences between groups are indicated by asterisks (***$p < 0.001$).

the diet ($F_{(1,52)} = 59.30$; $p < 0.001$), as well as by the daily system biomass factor ($SysBio_d$) ($F_{(1,56)} = 15.79$; $p < 0.001$). Prior to mechanical filtration, TSS levels in the + Cork treatment were more than three times higher than in the Control group (+Cork: 16.00 ± 1.18 mg L^{-1}; Control: 4.65 ± 0.70 mg L^{-1}), corresponding to an increase of approximately 244% (Cohen's d = 2.07; $\eta^2 = 0.53$). Post-mechanical filtration, the applied model revealed that the cork treatment resulted in significantly lower TSS concentrations than the Control (+Cork: 1.83 ± 0.12 mg L^{-1}, Control: 2.18 mg L^{-1} ± 0.20, $F_{(1,55)} = 4.71$; $p = 0.034$), a reduction of 16% (Cohen's d = 0.39; $\eta^2 = 0.08$), with $SysBio_d$ also demonstrating a significant effect ($F_{(1,55)} = 24.58$; $p < 0.001$) (Fig. 3A). Analyses of the BWW samples showed that systems fed with additional cork delivered significantly greater retention of solids by mechanical filtration, with backwash concentrations more than five times higher than in the Control group (+Cork: 1140.98 ± 110.30 mg L^{-1}; Control: 207.64 ± 22.40 mg L^{-1}, $F_{(1,60)} = 61.60$; $p < 0.001$), an increase of 499% (Cohen's d = 2.04; $\eta^2 = 0.51$) on the results from the standard commercial diet (Fig. 4A). The RE of the drum filters varied significantly between treatments, with the + Cork systems achieving 86.5%, more than double of the solids removed by the Control system (Control: 42.43 ± 3.28%; +Cork: 86.45 ± 3.23%, $F_{(1,59)} = 91.64$; $p = <0.001$) (Fig. 5A).

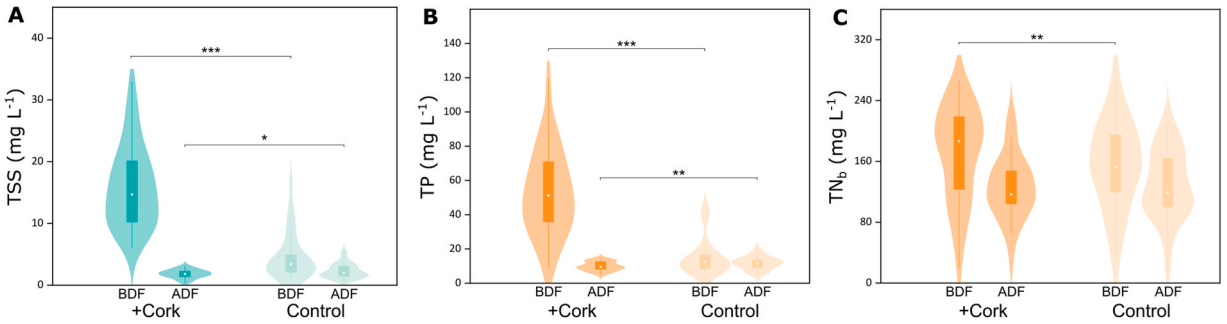

Fig. 3. Violin plots showing concentrations of (A) total suspended solids (TSS), (B) total phosphorus (TP), and (C) total nitrogen (TN_b) in water samples collected before (BDF) and after (ADF) drum filter during system regular operation under Control and + Cork treatments. Violin plots represent the data distribution, with the median (white dot) and interquartile range indicated. Statistically significant differences between groups are indicated by asterisks (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

3.4. Particle-bound nutrient removal and leaching

Cork supplementation significantly influenced TP concentrations in samples collected both before (+Cork: 52.71 mg L^{-1} ± 4.30; Control: 15.16 mg L^{-1} ± 1.87) and after (+Cork: 9.87 ± 0.47 mg L^{-1}; Control: 11.68 ± 0.66 mg L^{-1}) mechanical treatment ($F_{(1,62)} = 59.45$; $p < 0.001$ and $F_{(1,60)} = 6.57$; $p = 0.013$, respectively), with $SysBio_d$ also having a significant effect at both sampling points ($F_{(1,62)} = 14.69$; $p = 0.0003$ and $F_{(1,60)} = 110.55$; $p < 0.0001$, respectively) (Fig. 3B). Prior to filtration, TP concentrations in the + Cork group were approximately 248% higher than in the Control (Cohen's d = 2.13, $\eta^2 = 0.19$), indicating an extremely large effect size. After filtration, TP levels were around 15.5% lower in the + Cork group (Cohen's d = 0.56, $\eta^2 = 0.10$) than the Control. TN_b concentrations were significantly higher prior to mechanical treatment in the + Cork group (+Cork: 170 ± 10.94 mg L^{-1}; Control: 155.68 ± 10.01 mg L^{-1}, $F_{(1,62)} = 5.35$; $p = 0.024$), representing an increase of approximately 9.2% compared to the Control (Cohen's d = 0.24; $\eta^2 = 0.079$), indicating a small but still meaningful effect. However, after mechanical treatment, no significant differences were observed between groups (+Cork: 126.42 ± 7.38 mg L^{-1}; Control: 129.08 ± 7.79 mg L^{-1}, $F_{(1,62)} = 0.70$; $p = 0.407$), with only a 2.1% difference (Cohen's d = 0.06; $\eta^2 = 0.011$) (Fig. 3C). $SysBio_d$ significantly influenced concentrations of both TP and TN_b ($F_{(1,62)} = 75.13$; $p < 0.0001$ and $F_{(1,62)} = 80.90$; $p < 0.0001$, respectively). The cork treatment resulted in a greater concentration of particulate P (+Cork: 86.09 ± 0.70%; Control: 49.68 ± 2.22%, $F_{(1,47)} = 87.09$; $p < 0.0001$) and N (+Cork: 37.08 ± 1.69%; Control: 29.04 ± 2.09%, $F_{(1,62)} = 8.09$; $p < 0.006$) before mechanical filtration (Fig. 6 A). This resulted in more efficient removal of both nutrients ($F_{(1,5)} = 89.85$; $p = 0.0002$ and $F_{(1,48)} = 4.55$; $p = 0.038$, respectively) (Fig. 5B and C), and a consequent reduction in leaching potential ($F_{(1,60)} = 127.50$; $p < 0.0001$ and $F_{(1,62)} = 8.09$; $p = 0.006$, respectively) (Fig. 6B).

In BWW samples, the + Cork treatment resulted in TP concentrations 311% higher than the Control, representing a significant difference (+Cork: 334.01 mg L^{-1} ± 39.54; Control: 81.39 mg L^{-1} ± 9.54, $F_{(1,60)} = 28.31$; $p < 0.0001$) (Cohen's d = 1.58; $\eta^2 = 0.32$) (Fig. 4B). A similar trend was observed for TN_b, with a significant 68% increase in the + Cork treatment (+Cork: 580.94 ± 44.09 mg L^{-1}; Control: 345.38 ± 20.58 mg L^{-1}, $F_{(1,60)} = 18.90$; $p < 0.0001$) (Cohen's d = 1.22; $\eta^2 = 0.24$) (Fig. 4C), and a significant $SysBio_d$ effect ($F_{(1,59)} = 7.35$; $p = 0.009$).

3.5. Water chemistry and biofilter efficiency

The supplementary cork resulted in a significant reduction of 10% in CO_2 levels (Table 5). A reduction in TAN concentrations was also observed after the biofilter in the cork-treated group, but this did not translate into a significant improvement in TAN removal efficiency. All other monitored nitrogen-related parameters were unaffected by the dietary treatment (see Supplementary Material S4). A comprehensive summary of relevant water quality parameters monitored throughout the experiment is provided in Table 5, while Table S5 (see Supplementary Materials) provides the relevant parameters during each experimental phase.

4. Discussion

This study investigates the potential of incorporating cork into a commercial RAS diet to facilitate faecal removal and improve solid waste management in a semi-technical system. Our findings align with the initial hypothesis that the inclusion of 3% cork in the diet yields faecal casts less dense than water, which float to the surface, where they can be efficiently and immediately transported to the mechanical treatment, thereby optimising its performance. These improvements include enhanced removal of TP and TN_b, which are retained within the solid waste stream, thus reducing the opportunity for nutrient leaching compared with the control group. Demonstrated for the first time in Atlantic salmon produced in a low-water-exchange system, these results are consistent with previous studies with rainbow trout (Schumann et al., 2016; Unger et al., 2015) and further confirm the efficacy of cork diets in enhancing solid and nutrient removal from RAS.

Within 24 h of first feeding, floating faeces became evident on the surface of all tanks receiving the cork-enriched diet. The waste was effectively removed via tank surface overflow stream, facilitated by the circular water flow and specially installed pipes leading

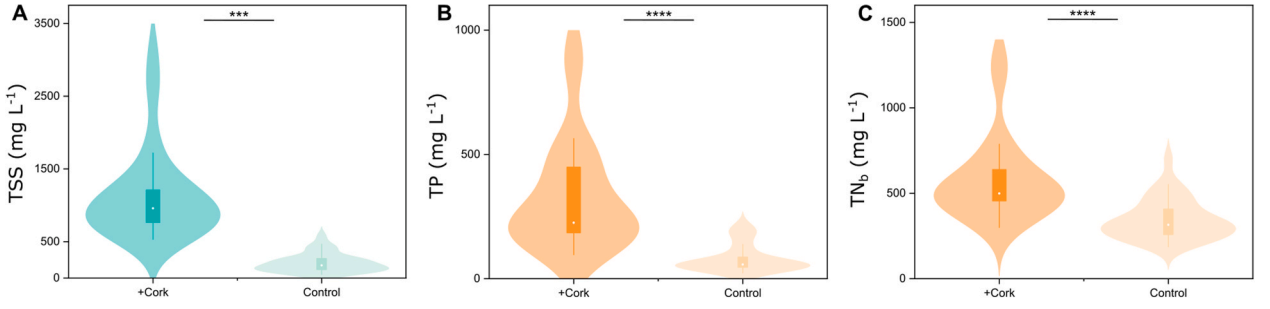

Fig. 4. Violin plots showing the concentrations of (A) total suspended solids (TSS), (B) total phosphorus (TP), and (C) total nitrogen (TN_b) in backwash water (BWW) under Control and + Cork treatments. Violin plots illustrate the data distribution, median (white dot), and interquartile range. Higher concentrations of TSS, TP, and TN_b were observed in the + Cork treatment compared with the Control. Statistically significant differences between groups are indicated by asterisks (***$p < 0.001$, ****$p < 0.0001$).

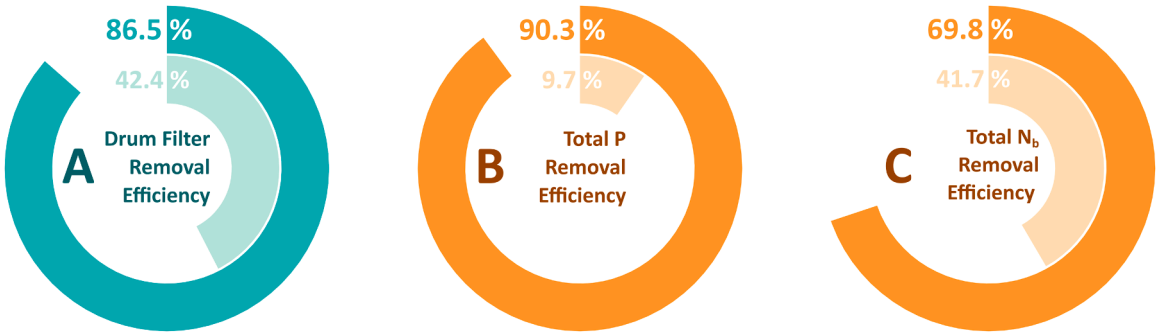

Fig. 5. Removal efficiencies (RE) of (A) total suspended solids (TSS), (B) total phosphorus (TP), and (C) total nitrogen (TN) for the Control and + Cork treatments.

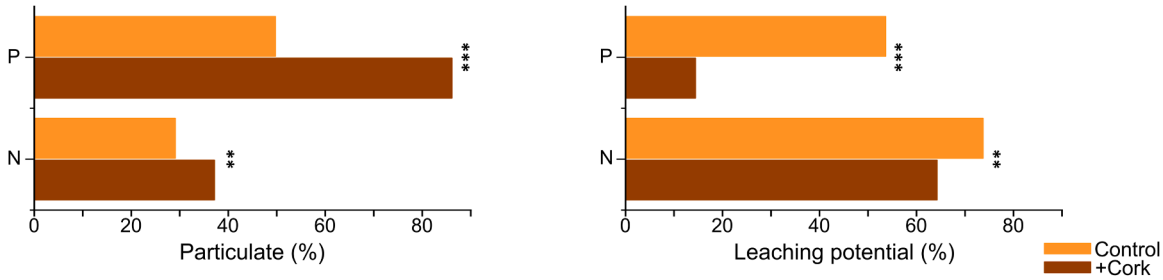

Fig. 6. (A) Bar plot showing particulate content (%) of P and N under control and + Cork treatments. (B) Bar plot showing the leaching potential (LP, %) of phosphorus (P) and nitrogen (N) under Control and + Cork treatments. Bars represent total estimated LP for each nutrient. Statistically significant differences between groups are indicated by asterisks (**$p < 0.01$, ***$p < 0.001$).

Table 5
Water quality measurements and removal efficiencies of TAN and NO_2-N of different RAS during Control and +Cork treatments.

Diets	CO_2 (mg L^{-1})	NH_4^+-N (mg L^{-1})	TAN BBF (mg L^{-1})	TAN ABF (mg L^{-1})	NO_2-N BBF (mg L^{-1})	NO_2-N ABF (mg L^{-1})	NO_3-N BBF (mg L^{-1})	NO_3-N ABF (mg L^{-1})	TAN RE (%)	NO_2-N RE (%)
Control	8.89 ± 0.27[a]	0.23 ± 0.01	0.21 ± 0.02	0.13 ± 0.01[a]	0.12 ± 0.04	0.09 ± 0.03	91.26 ± 2.60	92.64 ± 2.60	39.83 ± 1.10	26.52 ± 2.20
+Cork	7.95 ± 0.27[b]	0.24 ± 0.01	0.20 ± 0.02	0.12 ± 0.01[b]	0.10 ± 0.04	0.08 ± 0.03	95.11 ± 2.60	95.75 ± 2.60	39.91 ± 1.10	25.78 ± 2.19
Model effects (*p*-value)										
Treatment	< 0.0001	0.231	0.184	0.027	0.052	0.094	0.296	0.399	0.962	0.441
$SysBio_d$	< 0.0001	< 0.0001	0.101	0.378	0.0002	0.0017	< 0.0001	< 0.0001	0.062	0.133
Treatment*$SysBio_d$	0.385	0.0038	0.440	0.283	< 0.0001	< 0.0001	0.250	0.241	0.379	0.095

Values are presented as LS means ± SE. Superscript letters indicate significant differences among treatments ($p < 0.05$). CO2 and NH4 + -N were continuously monitored throughout the experiment, while NO2–N, NO3—N and TAN were measured periodically (3 times per week) before and after the biofilter.

directly to the mechanical drum filter (see Supplementary Material S2). This process did not incur additional energy costs and did not cause any noticeable effects on animal behaviour throughout the experiment, consistent with the findings of Schumann et al. (2016) for rainbow trout.

The effective ingredient, cork, is characterised by a distinctive honeycomb-like, closed-cellular structure with unique mechanical and chemical properties (Vilela et al., 2013), including low friability, very low liquid permeability, high elasticity, chemical inertness, low density, and resistance to microbial degradation (Pereira, 1988, 2015). Moreover, being indigestible and extraordinarily resilient in the digestive system of carnivorous fish, it is an ideal candidate to be considered as a density-reducing dietary additive. Feed pellets containing cork exhibited excellent performance and were readily accepted by the salmon. Despite an inevitable reduction in dry matter digestibility due to the inclusion of indigestible material, fish on the cork-enriched diet exhibited significantly better growth (SGR and TGC) but no significant food uptake. In contrast, Unger et al. (2015) reported no effect on growth in a commercial setting when testing a feed with 2.5% cork addition, but did observe increased feed intake. Both outcomes, however, are consistent with the

underlying hypotheses, suggesting that improvements in water quality associated with the cork supplementation may help mitigate possible negative effects of the slight nutrient dilution introduced by the indigestible cork, potentially reducing physiological stress and supporting better performance. Although no improvements in the biofilters' removal efficiencies have been reported in the present study, significant reductions in TSS, TAN_{ABF}, and CO_2 levels were observed. These findings will be discussed further in the text.

It is considered likely that the incorporation of indigestible and resilient cork granules into high-energy extruded aquaculture feed pellets might stimulate duodenal receptors involved in the regulation of gastric evacuation, thereby prolonging stomach retention time. This may additionally influence both gastric and pyloric sphincter contractions, resulting in larger items spending longer in the stomach in an attempt to grind them into smaller particles (Sveier et al., 1999). This enhanced retention may promote more efficient enzymatic digestion before the emptying occurs, thereby improving nutrient absorption from the digestible fraction of the cork-enriched pellets (Azaza, M. S. et al., 2010), as indicated by the increased PER observed in the cork-supplemented group. Such a response echoes a similar physiological mechanism previously observed in fish ingesting large food items, high-energy diets or low-friability prey (Jobling, 1987). For example, the ingestion of *Tenebrio molitor* larvae, which are both energy-rich and minimally friable thanks to a chitin-rich exoskeleton, has been reported to slow down gastric evacuation in brown trout (Jobling, 1987; Elliott, 1972). These observations suggest a potential additional benefit of cork-enriched diets, optimising feeding in commercial scenarios, thereby further reducing waste and mitigating impacts on water quality in RAS operations (Gao et al., 2019). Additionally, the inclusion of cork in the diet had no adverse effects in any of the measured parameters for Atlantic salmon, reinforcing similar results for rainbow trout (Unger and Brinker, 2013; Unger et al., 2015; Schumann et al., 2016). Further investigations are, however, still required to assess the specific effects of cork granules on gastric tissue, emptying rates, apparent digestibility of specific nutrients, and digestive enzyme activity in order to fully understand their physiological and nutritional implications in salmonids.

It is well established that effective treatment of solids in RAS requires efficient mechanical treatment (Timmons et al., 2018). In order to maximise the removal of the large quantities of microparticles inevitably generated by regular RAS operation, it is generally recommended that the microscreen rating of the drum filter be reduced (de Jesus Gregersen et al., 2024). However, doing so leads to an increase in investment and energy costs for RAS facilities (Dolan et al., 2013; Fernandes et al., 2014). The creation of "floating faeces" opens a whole new approach to solid management in RAS. The addition of cork to the feed immediately facilitates faecal removal with minimal tank modifications, thereby reducing exposure to disintegrative and leaching forces. The presence of a faecal binder further maximises faecal integrity during the operational process. As a result, larger solids are swiftly removed, the generation of smaller particles is reduced, and leaching of key nutrients into the system is minimised. These improvements could potentially allow facilities to maintain larger micro-screen rates and even reduce the operational costs of mechanical treatment while improving water quality within the systems, up to a best-case scenario where only 1% of the flow needs to be treated with a modified endless belt system (Unger et al., 2015), thereby increasing system stability.

For our experimental treatment, as well as for the previously published studies using cork-enriched feeds in salmonids (Unger and Brinker, 2013; Unger et al., 2015; Schumann et al., 2016), the inclusion of small amounts of granular cork in the diets significantly and effectively reduced faecal density to values below that of water (< 1.00 g cm^{-3}). This effect was enhanced with prolonged immersion in water. The reduction in faecal density remained consistent during the entire experiment, demonstrating that a 3% dietary cork was sufficient to secure the desired effects in the tested animals. Contrary to the findings of Schumann et al. (2016), who reported a decline in faecal density associated with fish size, no such decline was observed for the Atlantic salmon in this experiment. However, the fish in our study span a smaller size range. To address such a decline, it may be necessary to optimise cork granule size or inclusion level to fish size, potentially increasing efficiency for animals of other size classes or species.

Systems where cork diets are consistently fed have demonstrated their ability to retain and remove substantially higher quantities of solid particles larger than 100 μm—the mesh size deployed on the drum filters. This performance can be attributed to the rapid surface removal process, which minimises fragmentation under system turbulence (Brinker et al., 2005; Schumann et al., 2016). TSS analysis of water samples collected before and after the drum filter showed that feeding fish a cork-enriched diet resulted in a RE of 86.5%, more than double that removed from the Control RAS. In a similar study, Schumann et al. (2016) reported a RE of 59% using the same micro-screening rate in an RAS rearing rainbow trout fed a 2.5% cork-enriched diet—demonstrating the same doubling effect as seen in our experiment. However, while their cork treatment resulted in greater TSS concentrations before mechanical filtration, no differences were observed after the drum filter. In contrast, our experiment achieved not only a higher RE with the cork treatment but also a significant reduction in particulate matter remaining in the recirculating water compared to the control system.

In a commercial semi-technical RAS, Unger et al. (2015) demonstrated that although the drum filter performed more efficiently with a 30 μm micro screen—achieving an RE of 80.2% when fish were fed a cork-enriched diet—a 100 μm mesh was still sufficient to nearly double the RE in the cork treatment (56.6%) compared to the control (29.0%). In the present study, a modest 0.5% increase in dietary cork content resulted in an RE of 86.5%, approximately 6% higher than that reported in Unger's study, which used a finer filter gauze. This reflects the effectiveness of cork supplementation in improving solid removal in full-RAS, even in less costly drum filter operations. In the same study, the authors demonstrated that cork-fed systems resulted in 78.3% of floating solids being efficiently removed by a prototype mechanical surface separator that, in continuous operation, added only about 1410 kWh to annual operational energy costs, compared to around 9570 kWh of a continuously running drum filter, depending on system size. Similarly, Schumann et al. (2016), using a surface pipe removal method identical to that employed in this study, reported TSS concentrations in the backwash water approximately five times higher than in the Control, with an estimated 56% of the total system solid load removed via tank overflow. Despite the RO obtained in our study falling short of initial expectations based on sampling observations, the simple surface removal device, operated at no additional energy costs, combined with the cork-enriched feed, still managed to remove 60.3% of the predicted excreted material and accumulated nearly five times more TSS in the cork system's waste stream. To better assess the effectiveness of such devices and improve the accuracy of future analyses, it is essential that measurements be more precisely aligned

with feeding times and fish evacuation rates. This would provide a better understanding of the mechanism's contribution to the overall system efficiency. Nonetheless, we consider these low-tech devices a valuable and effective addition in terms of energy savings and overall system performance for the purpose under study. These devices can be easily installed within existing RAS operations. This method has been demonstrating its effectiveness in systems originally designed for solid removal via sedimentation; however, it is particularly advantageous in systems specially engineered for its purpose, especially in land-based facilities, but also in net pens, where the sedimentation of faecal excretions poses environmental concerns.

Feeding Atlantic salmon a cork-enriched diet effectively preserves critical nutrients—TP and TN_b in the particle-bound fraction. Exposure to leaching is not only reduced through almost immediate removal but also because larger and more cohesive particles present a smaller liquid-solid contact area, as described by Brinker et al. (2005). In high-intensive RAS operations, the accumulation of uneaten feed and faeces can lead to increased levels of nitrogen-based pollutants, which can potentially exceed the capacity of bioreactor treatment and negatively impact the cultured organism's performance and welfare (Li et al., 2023). Fish typically retain only 15–40% of P applied in feeds, while over 50% is excreted, and more wasted in uneaten feed (Yogev et al., 2020). Although phosphorus does not represent the same immediate threat to fish as nitrogen-based compounds, excess levels in RAS can contribute to eutrophication, triggering a cascade of negative effects, such as suppression of nitrification regarding heterotrophic dominance, algal blooms and clogging of pipes and bioreactors (Hua and Bureau, 2005; Luo, 2022). These challenges emphasise the importance of integrated nitrogen and phosphorus removal strategies in RAS, a benefit already demonstrated in studies using cork-enriched feeds (Unger et al., 2015; Schumann et al., 2016). In our study, the cork treatment significantly improved TP and TN_b retention in the waste stream, thereby improving the potential of RAS waste as a recoverable nutrient source. However, unlike the findings from a commercial-scale study (Unger et al., 2015), which reported substantial gains in biofilter efficiency and stability using a cork-enriched diet, improvements in nitrification in the present experiment were not as clear as expected. While significantly lower concentrations of CO_2 and TAN_{ABF} were observed in the +Cork treatment, other parameters, including TAN_{BBF} and TAN removal efficiency (RE%), remained unaffected. These outcomes are most likely attributable to the oversized biofilters used in the experimental setup, which probably masked expected differences between treatments. Consistent with Schumann et al. (2016), the daily feeding load (approximately 2 kg day^{-1}) in our experimental systems was well within biofilters' capacity (< 70% of MBBR capacity), allowing both control and cork-related systems to maintain high removal efficiencies regardless of treatment. Still, the lower TAN_{ABF} observed in the cork-treated system suggests a direct effect of reduced organic input into the biofilter, which would be more evident if feeding rates had matched its capacity. By improving solids removal upstream, the cork-enriched diet likely reduced the circulation of finer particulate organic matter in the system, thereby decreasing the continuous release of ammonia into the water loop. This lower organic load appears to have created slightly more favourable conditions for nitrifiers by limiting competition with heterotrophic bacteria for oxygen (O_2) and space (Michaud et al., 2009, 2013; Rojas-Tirado et al., 2018). Supporting this, Fernandes et al. (2025) recently demonstrated that even a modest increase in TSS within concentration ranges considered safe for salmonids (from 1 to 7 mg L^{-1}) has the potential to alter biofilter microbial communities, promoting competition from heterotrophic bacteria and, consequently, reducing the biofilters' nitrifying capacity. It seems likely that systems equipped with fixed-bed bioreactors—widely used in commercial setups, yet particularly sensitive to clogging and performance degradation induced by fines (Sorrentino et al., 2024)—may benefit more from this cork diet approach. By reducing fines and nutrient load, a system fed a cork-enriched diet can reduce the risk of clogging or overwhelming biofilms, potentially leading to steadier water flow and healthier biofilm activity in fixed-bed bioreactors.

In RAS, CO_2 represents a particularly critical aspect of water quality management, as prolonged exposure to elevated concentrations can compromise fish growth, health and overall system performance (Aslam et al., 2019; Mota et al., 2018). Moreover, the removal of CO_2 represents one of the most energy-dependent and costly processes in RAS operations, not only limiting fish densities but also influencing flow rates and, consequently, increasing energy demand for pumping (Mota et al., 2018). The reduction in dissolved CO_2 observed in the cork treatment is most likely related to the small quantities of particulate material escaping the mechanical filtration when compared to a standard scenario. In systems with high rates of water reuse, the buildup of fine particles leads to an increase in the surface area available as a substrate for bacteria to proliferate and disseminate within the water loop. This promotes an increase in O_2 consumption and, consequently, the CO_2 levels in the rearing water (de Jesus Gregersen et al., 2018; Petersen et al., 2017). Gorle et al. (2018), while studying hydrodynamics and water quality in RAS, observed that O_2 respiration rates doubled as TSS concentration increased in the tanks, even when the feeding rate was maintained. This is highly pertinent for commercial RAS and for the implementation of cork-enriched feeds in large-scale operations. Reducing TSS levels in commercial systems while maintaining or even optimising the feeding rates could considerably reduce the O_2 input required to meet fish demand while producing considerably less CO_2, thereby improving production while optimising costs. The current study did not determine O_2 respiration rates or measure TSS in the rearing tanks. However, these should be a consideration for future studies.

Overall, the notable improvements associated with dietary cork, in particular the enhanced solid removal via surface skimming, demonstrate the great potential of this approach to improve waste management in RAS. Furthermore, its implementation in already existent RAS and other aquacultural settings is a straightforward process, requiring only minimal modifications. Cork granules, a major by-product of the cork industry, offer a sustainable and value-added application when incorporated into aquafeeds. However, long-term trials in commercial-scale systems would be beneficial for further validating its effects on production performance and on long-term system microbiology. This work supports the ongoing efforts of industry and academia to convert aquaculture waste into valuable products, including biogas and agri-fertilisers. By integrating cork granules into fish diets, RAS operations can shift from waste disposal to resource recovery, thereby enhancing the sector's sustainability, reducing operational costs, and contributing more effectively to a circular economy.

5. Conclusion

The first application of the "floating faeces" concept in a full-RAS for the freshwater phase of Atlantic salmon revealed promising results for solid waste management in systems reusing water. The incorporation of 3% cork granules into RAS-specific diets effectively reduced faecal density, thereby permitting more efficient removal of solids via surface skimming at no additional energy expenditures. This resulted in a remarkable 86.5% solid removal efficiency via mechanical filtration. In addition, the diet supplemented with cork also led to improved fish growth and protein retention, probably as a result of improved water quality, reflected by the reduced levels of TSS, TAN and CO_2. The outcomes of the present study reinforce the potential of cork-enriched diets as a low-cost, sustainable approach to optimising both solid waste management and water quality in RAS.

CRediT authorship contribution statement

Alexander Brinker: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mark Schumann:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sara de Sousa e Brito:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used DeepL Write (www.deepl.com) in order to check grammar and punctuation, and to receive guidance on restructuring and breaking up longer sentences for better readability. After using this AI-assisted tool, the authors reviewed, evaluated, and reworded the suggestions as needed, ensuring that no content was directly copied and used without critical revision, and take full responsibility for the content of the publication.

Funding statement

This work was funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 956481.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sara de Sousa e Brito reports financial support was provided by European Union. Prof. Dr. Alexander Brinker has patent #PCT/EP2012/068118 licensed to Landwirtschaftliches Zentrum Baden-Württemberg (LAZBW). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Jørgen Holm for his support for the experiment, Anders Lindquist for his exemplary technical assistance in preparing the experimental diets, Helga Bentele for her exceptional technical help with the laboratory analysis and Tamara Wind for her support with fish husbandry. We also thank Amy-Jane Beer for the scientific language editing.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.anifeedsci.2026.116898.

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