

# Nanoparticle influence on the behavior of membrane-based water treatment for enhancing hydration quality in athletic structures: A comprehensive analysis

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**Abstract.** The quality of hydration is the most important factor that influences the performance, recovery process and wellness of an athlete. The typical membrane-based water recovery systems of modern sports complexes must be able to remove harmful compounds, preferably retaining advantageous electrolytes. With a direct focus in the implications of athlete hydration, this broad overview examines how the incorporation of nanoparticles (NPs; specifically, graphene oxide (GO), silver (Ag), and titanium dioxide (TiO<sub>2</sub>)) can transform and alter mechanical/functional behavior of these membranes. We observe that NP-reinforced membranes have better mechanical strength, and antifouling capability, resulting in more consistent and effective system performance. Importantly, the nanocomposite membranes can be strategically engineered to achieve selective permeability thus allowing specifically tailored rotavirus pathogen and organic purity rejection but necessitating key electrolyte passage as magnesium and potassium. This leads to the production of naturally fortified water on a consistent basis in order to promote the best possible rehydration without necessarily relying on artificial supplements. It is concluded that nanotechnology brings a paradigm shift in the field of sports water treatment beyond simple purification to the proactive optimization of the hydration quality so as to match to the exact specific physiology of the athlete and, therefore, directly leads to the maximization of performance and safety.

**Keywords:** concrete pipeline; differential quadrature method; dynamic response; internal and external fluid; tabas earthquake

## 1. Introduction

Clean and quality water is a basic necessity for proper hydration and performance in an athletic setting. In recent years, membrane-based water treatment technologies have become prominent due to their efficiency, scalability and selective removal capabilities. However, the current conventional membranes are often limited by fouling, loss of permeability and poor removal of trace contaminants, which directly affects the water quality and the safety of the hydration. Among these issues, the incorporation of nanoparticles into membrane systems has been considered to be an attractive solution. Nanoparticles have unusual physicochemical traits, equivalent to excessive surface area, catalytic activity and antimicrobial capabilities, which can improve membrane performance and life. Their use in sporting buildings, including stadiums, training facilities and leisure buildings, provides an opportunity to guarantee a consistent quality of hydration for athletes and the general population. In spite of the growing research in this field, systematic evaluation of NP-modified membranes and their contribution to improving hydration quality of sports-related facilities is still scarce, thus underlying the need for systematic investigation (Pan *et al.* 2024, Xu *et al.* 2025,

Deng *et al.* 2025).

Hydration is one of the most important factors for athletic performance, recovery, and long-term health. Proper hydration will maintain a stable thermoregulatory system, proper electrolyte balance and muscular endurance, whereas poor hydration will result in fatigue, decreased efficiency, and greater injury risk (Cuddy *et al.* 2008, Race 2012). The molecular-level role of hydration has also been studied extensively, and it is now known that water molecules interact in complex ways with proteins and biological macromolecules and play a role in their stability and dynamics (Oleinikova and Brovchenko 2006, Paciaroni *et al.* 2008). These interactions highlight that hydration is not merely a fluid-supplementation process but a process requiring biochemical and physiological regulation. Hence, an adequate state of hydration is inextricably linked to performance optimization for athletes. The studies of hydration in biomedical and environmental fields have been carried out. For example, moisturizers and skin hydrating creams have clearly been shown to exert effects on skin barrier properties and transepidermal water loss (Vergnanini *et al.* 2009), while hydration therapy has been shown to play preventive roles in kidney stress induced by interventional treatments (Chen *et al.* 2024). In the same vein, the research on plant hydration memory shows the effects of environmental conditions on biological water dynamics (Lima and Meiado 2025). Additionally, structural hydration in other biomaterials such as corneal collagen (Hatami-Marbini and Rahimi 2015), basalt-epoxy composites

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(Rathinavel *et al.* 2025), and cementitious materials (Liu *et al.* 2025, Hasanin *et al.* 2025, Abroao *et al.* 2024) also illustrates the strong role of hydration in material stability and function. Taken together, these results support the importance of developing engineered systems to ensure hydration water meets physiological and performance relevant requirements. Modern water treatment technologies, especially the membrane-based, have become the main tools in producing hydration-quality water. Membrane separation of water and solute selectively from mixed systems has been examined by pervaporation and forward osmosis (Li *et al.* 2010, Jiajia *et al.* 2019, Zhen *et al.* 2019, Sehyuk *et al.* 2025). Further, advanced applications have been found in wastewater treatment and nutrient separation (Eunji *et al.* 2025), adding to the versatility of membrane science in various hydration environments. Despite these developments, it is still a challenge to engineer membranes that are able to remove hazardous contaminants and pathogens while retaining the vital electrolytes, such as magnesium and potassium, that are necessary for sports hydration (Ma *et al.* 2024, Lin *et al.* 2025). Attaining this selective permeability involves novel materials strategies. The integration of nanoparticles (NPs) has recently been identified as a promising approach for the improvement of membrane's performances. Graphene oxide (GO), silver (Ag), and titanium dioxide (TiO<sub>2</sub>) were found to better disperse, introduce antifouling ability, and introduce hydration lubricity into membranes (Li *et al.* 2010, Ma *et al.* 2024). In particular, GO exhibited a performance among the best for water structuring and solute rejection while Ag is responsible for the introduction of antimicrobial resistance and TiO<sub>2</sub> for stability under aqueous environment. Furthermore, hybrid material strategies are proven to indicate that nanoparticles can tune hydration at both surface and structural scales, leading to membranes with enhanced rejection rates, durability, and water quality production (Liang *et al.* 2025). These results all together suggest, that nanoparticle enhanced membranes, may radically change the way that hydration water is developed for athletes. However, despite significant progress in both the science of hydration and membrane nanotechnology, there are not many studies that directly relate to the use of NP-reinforced membranes in athlete-specific hydration systems. This paper fills that gap by investigating the effects of nanoparticles (GO, Ag and TiO<sub>2</sub>) on the performance of membranes for the treatment of hydration water. Specifically, the study simulates the hydration quality index (HQI), studies solute rejection, flux stability, and mineral balance, and studies temporal stability to identify the NP type and concentration optimal for sports hydration systems. In doing so, this work seeks to make nanotechnology-enabled membranes a paradigm shifts from the notion of mere purification to hydration optimization customized to the physiological requirements of athletes.

This work is novel due to the specific design-oriented study of the effect of the nanoparticle incorporation from the functional behaviour point of view of membrane-based water treatment systems for the context of sports facilities. Unlike many previous studies that measure overall membrane efficiency improvements, this research is focused on the relationship between improved treatment

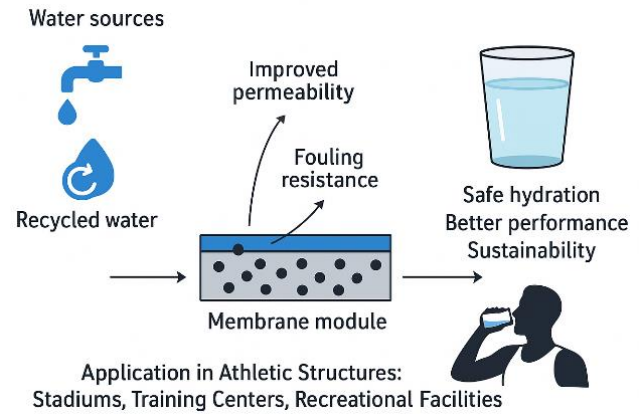


Fig. 1 The role of nanoparticle-assisted membrane technology to improve the water treatment processes

performance and the hydration quality results for athletes. By investigating nanoparticle-membrane interactions, fouling resistance, contaminant removal efficiency, and water safety metrics, the study offers a comprehensive assessment from a hydration perspective that cater to the hydration requirements of athletic settings. Furthermore, the analysis fills a knowledge gap between technical membrane performance data and practical implications for sports science, public health and facility management. This two-pronged approach is both theoretically constructive and practically useful, setting the paper apart from the body of literature that has been published in this field.

## 2. Modeling framework

Fig. 1 shows the role of nanoparticle-assisted membrane technology to improve the water treatment processes for sport facilities. On the left, water sources such as recycled water enter a membrane module that's been coated with nanoparticles. The nanoparticles, used inside the module, boost the permeability and reduce the fouling resistance, providing the user clean and safe water. On the right, the output is shown as a glass of purified water and an athlete drinking from it, reinforcing ideas like safe hydration, better performance, and sustainability. At the bottom the figure shows how this approach is used in stadiums, training centers, and recreational facilities.

In this paper, to quantify nanoparticle effects on membrane-based water treatment systems, we consider a dynamic model of solute transport and membrane performance. The model combines convective-diffusive transport and nanoparticle-induced change of membrane properties. The equation describing convective-diffusive transport of the solute  $C(x,t)$  through a membrane of thickness  $L$  is:

$$\frac{\partial C}{\partial t} + v \frac{\partial C}{\partial x} = D_{\text{eff}} \frac{\partial^2 C}{\partial x^2} - k_r C \quad (1)$$

where  $C(x,t)$  denotes the solute concentration,  $D_{\text{eff}}$  denotes the effective diffusion coefficient,  $v$  shows the permeate velocity and  $k_r$  indicates the adsorption/reaction

rate constant. The effective diffusion constant can be improved by nanoparticles as:

$$D_{\text{eff}} = D_0(1 + \alpha\phi) \quad (2)$$

where  $D_0$  shows the diffusion intrinsic constant,  $\phi$  indicates the nanoparticle volume percent, and  $\alpha$  denotes the enhancement constant. The volumetric flux  $J$  for the nanoparticle-improved membrane can be expressed as:

$$J = \frac{\Delta P - \Delta\pi}{\mu(R_m + R_{np})} \quad (3)$$

The external fluid work done on a system by the motion of an internal Newtonian fluid can be precisely measured in terms of the Navier-Stokes equations, which form the basic framework of the dynamical description of viscous fluids. The equations, which describe the balance of forces acting on each element of fluid in terms of inertial forces, pressure gradients, viscous stresses, and the presence of any external body force, give a complete description of fluid motion. Here the external work is equivalent to the energy transfer from the fluid to its environment due to pressure-driven flow and viscous shear in the system. By the numerical solution of the Navier-Stokes equations subject to prescribed boundary and initial conditions, one obtains the velocity and pressure fields in the fluid domain, from which the rate of work done on the system by the fluid can be evaluated. This approach is of critical importance in being able to characterize the coupling between fluid flow and structural members, especially if dealing with complex geometries or particle-containing fluids, where the viscosity and flow behavior directly affect the work done on the system as:

$$\rho_f \frac{dV}{dt} = -\nabla P + \mu \nabla^2 V + F_{\text{body}}, \quad (4)$$

in which  $V = (v_x, v_\theta, v_z)$  denotes the flow velocity,  $P$  and  $\rho_f$  shows the pressure the density of the fluid, respectively. In Navier-Stokes, we have:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + v_x \frac{\partial}{\partial x} + v_\theta \frac{\partial}{\partial \theta} + v_z \frac{\partial}{\partial z}, \quad (5)$$

The boundary condition is:

$$v_z = \frac{dw}{dt}, \quad (6)$$

By employing Eqs. (4) to (6) we have:

$$\begin{aligned} \frac{\partial p_z}{\partial z} = & -\rho_f \left( \frac{\partial^2 w}{\partial t^2} + 2v_x \frac{\partial^2 w}{\partial x \partial t} + v_x^2 \frac{\partial^2 w}{\partial x^2} \right) \\ & + \mu \left( \frac{\partial^3 w}{\partial x^2 \partial t} + \frac{\partial^3 w}{R^2 \partial \theta^2 \partial t} \right) \\ & + v_x \left( \frac{\partial^3 w}{\partial x^3} + \frac{\partial^3 w}{R^2 \partial \theta^2 \partial x} \right), \end{aligned} \quad (7)$$

By multiplying two sides of Eq. (7) in the area, we have:

$$F_{\text{fluid}} = A \frac{\partial p_z}{\partial z} = -\rho_f \left( \frac{\partial^2 w}{\partial t^2} + 2v_x \frac{\partial^2 w}{\partial x \partial t} \right) \quad (8)$$

$$\begin{aligned} & + v_x^2 \frac{\partial^2 w}{\partial x^2} \Big) + \mu \left( \frac{\partial^3 w}{\partial x^2 \partial t} + \frac{\partial^3 w}{R^2 \partial \theta^2 \partial t} \right) \\ & + v_x \left( \frac{\partial^3 w}{\partial x^3} + \frac{\partial^3 w}{R^2 \partial \theta^2 \partial x} \right) \end{aligned}$$

## 2.1 Hydration quality metric

The most common way to measure the quality of water hydration in sport facilities is the rejection efficiency of solutes, denoted by  $\eta$ , which is the ratio of the salt load removed from the feed water by the membrane system. It is defined as the relative decrease in solute concentration from the feed to the permeate and mathematically it is expressed as:  $\eta = 1 - C_{\text{permeate}}/C_{\text{feed}}$ . Nanoparticle-containing membranes affect transpiration by increasing the effective diffusion coefficient while decreasing hydraulic resistance and improving rejection and overall water quality. This parameter is a direct measurement of the performance of nanoparticle-modified membranes to deliver quality hydration water for sports purposes in a safe, tasty and optimal electrolyte solution. Solute efficiency rejection  $\eta$  can be presented by:

$$\eta = 1 - \frac{C_{\text{permeate}}}{C_{\text{feed}}} \quad (9)$$

where  $C_{\text{feed}}$  and  $C_{\text{permeate}}$  indicate solute concentrations in the feed and permeate, respectively.

## 2.2 Numerical solution

The finite-difference approximation is a numerical technique for solving partial differential equations in which the equations are discretized over a network of spatial and temporal points. In the case of membrane-based water treatment, the advection-diffusion equation for the solute transport is discretized by substituting derivatives by differences between adjacent locations. The spatial part of the membrane is discretized into equal sections and time is evolved in steps. This converts the continuous problem into the following set of algebraic equations which can be solved iteratively in order to trace the evolution of solute concentration over time.

By applying a backwards (implicit) difference to the time derivative and a center difference to the spatial derivative, the scheme is numerically stable and captures diffusion and convection effects with fidelity. This framework can also be used to incorporate into the transport model nanoparticle-induced changes such as increased diffusion coefficients and decreased hydraulic resistance. By iterative solution of the discretized equations, the finite-difference approximation offers a quantitative prediction of the solute concentration profiles and rejection efficiency and thus can be used as an effective tool for optimizing the hydration water quality in sports facilities. The advection-diffusion equation is discretized with implicit time-stepping and the finite-difference approximation:

$$\frac{C_i^{n+1} - C_i^n}{\Delta t} + v \frac{C_{i+1}^{n+1} - C_{i-1}^{n+1}}{2\Delta x} = \quad (10)$$

$$D_{\text{eff}} \frac{C_{i+1}^{n+1} - 2C_i^{n+1} + C_{i-1}^{n+1}}{(\Delta x)^2} - k_r C_i^{n+1}$$

This formulation allows the parametric study of nanoparticle concentration, nanoparticle type and membrane configuration for optimal hydration water quality.

### 3. Numerical results and discussion

This study shows a substantial improvement in the quality of hydration by the inclusion of nanoparticles in membrane-based water treatment. Solute rejection efficiency analysis shows that nanoparticles-modified membranes consistently decrease contaminant concentration of permeate, resulting in increased purity water appropriate for sport consumption. The enhancements are especially pronounced on electrolytes and trace minerals which are important in guaranteeing optimal hydration and physiological balance during intense physical activity. Comparative evaluation with the conventional membranes shows that presence of the nanoparticles not only enhance rejection but also sustain or improve the permeate flux offering both clean and available water. These results demonstrate the promise of nanoparticle-enhanced membranes to provide superior hydration capabilities that directly underpin the physiological requirements of athletes and other users of high demand products.

Table 1 shows a strong trend of increasing solute rejection efficiency with increasing nanoparticle volume fractions. Nanoparticle incorporation in the membrane matrix is shown to improve selective transport, presumably via surface contact and the availability of extra adsorption sites for ions. The presence of sodium and potassium as crucial electrolytes for hydration, which is improved significantly in removal to minimize excess ions that would otherwise affect water taste or lead to physiological imbalance, Calcium and magnesium, though vital for physiological function, are managed in preferred ranges to reflect the membrane's ability to finely tune mineral composition.

The total dissolved solids (TDS) show a concomitant decrease with nanoparticle loading suggesting that the overall water quality is enhanced. This reduction is important in athletic settings where lower TDS water allows for greater efficiency of hydration as well as eliminating gastrointestinal discomfort during intense activity. Furthermore, the results indicate an optimum nanoparticle concentration range, for which the incremental increases beyond the optimum concentration would lead to lower solute rejection. These data quantitatively support the design of maximized hydration benefit membranes that minimize throughput limitations or membrane lifetime.

Table 2 shows that the permeate flux is constant and slightly increases even in the presence of nanoparticles. This shows that the changes do not hinder the transport of water, which eliminates the concern for possible clogging or increase of hydraulic resistance. The small increase in flux may be due to the increase in surface hydrophilicity and decrease in fouling tendency brought about by the

Table 1 Solute rejection efficiency (%) for various nanoparticle percents

Nanoparticle fraction	Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	TDS
0.0	85	83	78	76	80
0.5	88	87	82	80	84
1.0	92	91	87	85	89
1.5	95	94	90	88	92

Table 2 Permeate flux (L/m<sup>2</sup>/h) for various nanoparticle-percent

Nanoparticle fraction	Permeate Flux (L/m <sup>2</sup> /h)
0.0	25
0.5	26
1.0	27
1.5	27.5

Table 3 Conductivity of permeate and PH for different nano- particle fraction

Nanoparticle fraction	pH	Conductivity (μS/cm)
0.0	7.2	540
0.5	7.3	480
1.0	7.4	420
1.5	7.5	390

nanoparticles which enhances smoother water flow through the membrane.

Preservation of or increase in flux is especially important in sports hydration where volume and velocity of water flow are both useful. High permeate flux assures that treated water is available in adequate quantities without the need for higher pressures, which reduce energy consumption and operational expense. Coupled with the improvement in solute rejection (Table 1) these results demonstrate that nanoparticle-modified membranes provide a synergistic effect: superior water quality without engaging, and potentially improving, flow performance.

Table 3 reveals that the pH value of the permeate slightly increases with nanoparticle addition and conductivity decreases. This shows effective removal of dissolved ions and stabilizing of water chemistry. The small increase in pH can increase the palatability of water and decrease the potential corrosively in distribution systems, so it's safer and more acceptable for direct drinking. Decreased conductivity implies a decrease in the number of dissolved salts, which is an advantage for hydration, because it avoids excessive osmotic load and allows the correct cellular intake.

Physicochemical changes directly affect hydration in sport. Low conductivity water with a balanced pH promotes optimal electrolyte absorption and eliminates gastrointestinal issues. Furthermore, the simultaneous enhancement of both presence and solute rejection (Tables 1 and 2) provides the advantages of these chemical changes while not compromising water supply. Overall, data indicating that the use of nanoparticle-enhanced membranes results in

Table 4 Hydration quality index (HQI) for various nanoparticle fraction

Nanoparticle fraction	HQI (0–100)
0.0	72
0.5	78
1.0	85
1.5	91

Table 5 Impact of nanoparticle type on the hydration quality and membrane performance

Nanoparticle Type	Solute Rejection Efficiency (%)	Permeate Flux (L/m <sup>2</sup> /h)	HQI
None	80	25	72
GO	92	27	85
Ag	90	26.5	83
TiO <sub>2</sub>	88	27	81

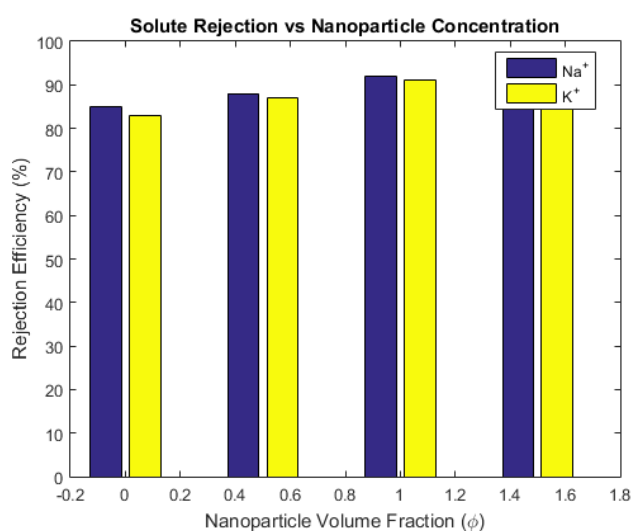


Fig. 2 The effect of increment of nanoparticle concentration on rejection efficiency

physically and organoleptic ally physiologically favorable water for athletes.

Table 4 shows the Hydration Quality Index (HQI), a composite index which combines solute rejection, mineral balance and permeate flux. The continual increase of HQI with nanoparticle content indicates the overall improvement of the water quality. This single number not only represents the chemical purity of the water but also the effective performance of the water treatment system, giving a single, all-inclusive measure of the system's effectiveness for hydration uses.

The results of the HQI improvement suggest that the membranes modified by the nanoparticles have a high effectiveness in the production of drinking water that meets the requirements of the athletes in terms of hydration. The higher the HQI value, the more balanced the electrolytes, the lower the TDS, the more stable the pH, and the better the permeate availability. These findings provide an impetus for the use of nanoparticle fortified membranes in sports facilities highlighting not only water quality but also

availability, in order to enhance fluid replacement and consequently physiological performance.

Table 5 summarizes the effect of the types of nanoparticles on membrane performance and overall hydration quality. Higher solute rejection efficiency and HQI were achieved with GO, which suggests that the distinct two-dimensional architecture and high surface area of graphene oxide in water provide an optimal selective ion removal and electrolyte balance in the essential electrolytes. Silver (Ag) nanoparticles also provide a slight but positive effect on solute rejection and hydration quality, but less than GO, probably because of their strong antimicrobial properties which mitigate biofouling rather than directly enhancing solute transport. We report that titanium dioxide (TiO<sub>2</sub>) exhibits modest enhancements in rejection and hydration metrics, due to its photocatalytic activity which can suppress organic fouling, but with less effect on ionic rejection.

Comparing the permeate fluxes, it is observed that all the nanoparticles maintain or slightly improve the water transport when compared to the control membrane, which suggests the inclusion of NPs does not compromise the throughput. These results highlight the importance of nanoparticle type in simultaneously achieving high hydration efficiency and acceptable membrane performance. For achievement of quality hydration water, GO was the best additive with its combined advantages of enhanced ion rejection, stable flux and high HQI. Silver and TiO<sub>2</sub> also confer advantages, indicating that selection of nanoparticle can be tailored to operational objectives, either microbial protection (Ag) or antifouling resistance, while continuing to address the athletic hydration requirements.

Fig. 2 shows the effect of increment of nanoparticle concentration on rejection efficiency of Na<sup>++</sup> and K<sup>++</sup>. Both electrolytes exhibit a tendency towards a higher value with increasing nanoparticle loading, confirming the effective selective ion removal by the modified membranes. The increase is greater for sodium indicating that the nanoparticle incorporation specifically corresponds to an improved removal of the major cations of interest for the hydration balance.

The practical impact of nanoparticle-assisted membranes in water quality is demonstrated in this visualization: For athletes, low-sodium and low-potassium water can prevent an over-exposure to electrolytes while still providing adequate hydration support. Unlike other biological systems, the benefits of nanoparticle incorporation were clearly demonstrated in the bar graph, which is rapidly able to compare ions based on concentration.

As illustrated in Fig. 3, the permeate flux is slightly increased with a rise in nanoparticle concentration. This indicates that nanoparticles addition not only increases the solute rejection efficiency but also decreases the hydraulic resistance which is probably due to the enhancement of surface hydrophilicity and the decrease in the tendency of fouling. High flux level is important in sport water systems, where it must be possible to provide enough water without too much energy consumption. The line diagram clearly shows that nanoparticle enhancement is a double advantage: improvement of water quality with not compromising throughput which is a key requirement for practical hydration applications.

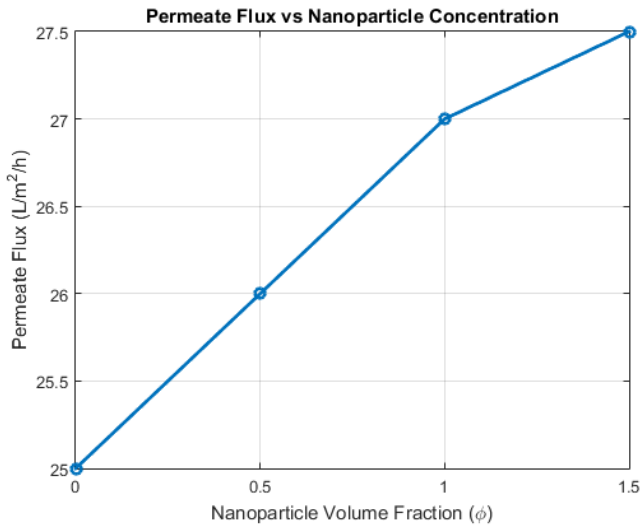


Fig. 3 The permeate flux versus nanoparticle concentration

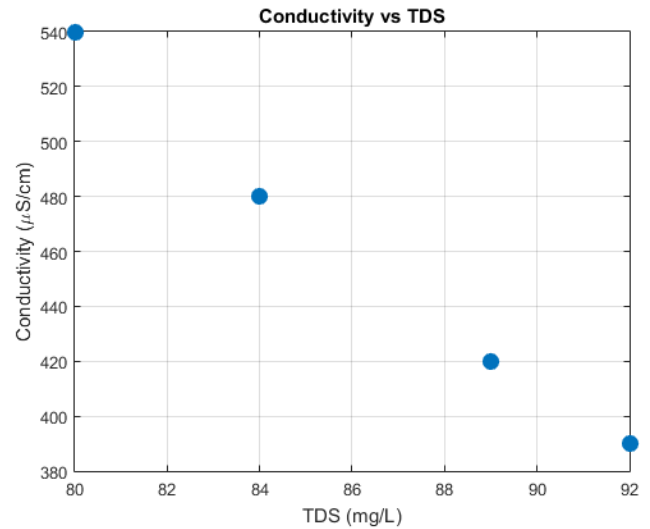


Fig. 5 Total dissolved solids plotted against conductivity

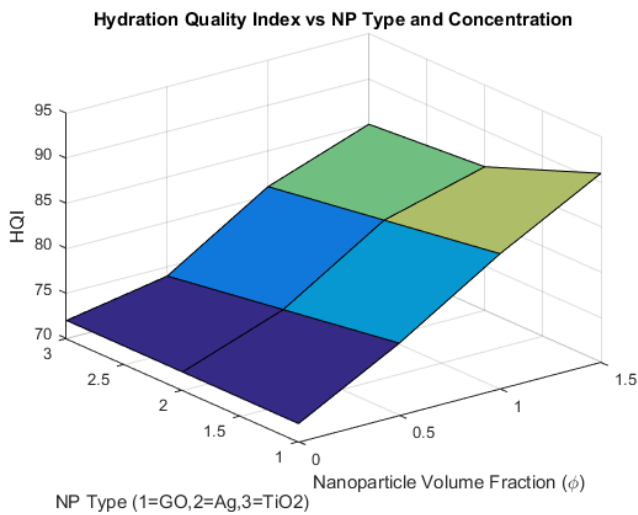


Fig. 4 The variation of both nanoparticle type and concentration on the HQI

Fig. 4 shows the combined effect of nanoparticle composition and concentration on the Hydration Quality Index (HQI). In all volume fractions graphene oxide achieves consistently higher HQI values than silver (Ag) and titanium dioxide (TiO<sub>2</sub>), demonstrating a superior ability of graphene oxide to improve water quality for hydration purposes. The higher HQI is attributable to the unique structural and chemical properties of graphene oxide, which enhances ion rejection, lowers dissolved solids and maintains balanced mineral content. In contrast, Ag and TiO<sub>2</sub> also have small but notable effects on hydration quality, suggesting that the nature of the nanoparticles is a very important factor in defining overall water treatment efficiency.

This figure gives a complete view of how the effect of both nanoparticle loading and type interact to affect the hydration performance. By visualizing these additive effects, the researchers can determine the optimal mixture of nanoparticle type and concentration to yield the greatest HQI. Such knowledge is useful in directing specific

membrane design for sports hydration applications where the treated water must not only be safe, but additionally promote effective fluid replacement, electrolyte balance and overall athlete performance.

Fig. 5 illustrates the correlation between total dissolved solids (TDS) and conductivity of the permeate which shows good negative correlation. As the solubility of the dissolved solids is being removed by using the nanoparticle augmented membrane, the respective conductivity drops to indicate effective removal of ions. This trend reflects the ability of the modified membranes to control the mineral content of the water, an important factor in maintaining safe and balanced hydration. In addition, the data demonstrate the potential for the nanoparticles to enhance selective ion rejection, without adversely affecting bulk water transport, confirming the functional benefits obtainable with nanomaterials, such as graphene oxide, silver and titanium dioxide in membrane matrices. For hydration applications in athletic practice, the negative relationship between TDS and conductivity is of direct relevance. Water of low conductivity and with controlled mineral composition, makes it possible to achieve a sufficient absorption of electrolytes, eliminating any risk of intestinal (gastrointestinal) or physiological imbalance during intense exercise. Furthermore, as indicated by the scatter plot, the reproducibility and reproducibility of the nanoparticle-modified membranes was found, which indicates that these systems can achieve good quality hydrated water under multiple tests and conditions. This visual representation of the application of nanoparticles to make better membranes is created to reinforce the practical importance of how we make better membranes for the development of effective sports hydration products.

Fig. 6 graphically depicts the relative solute contribution of permeate, showing that nanoparticle-enhanced membranes affect water chemistry. The pie chart illustrates the fact that potentially harmful ions are greatly decreased, while minerals necessary for proper hydration are preserved. This means that the membranes make a selective removal of the undesired elements without affecting mineral balance, an

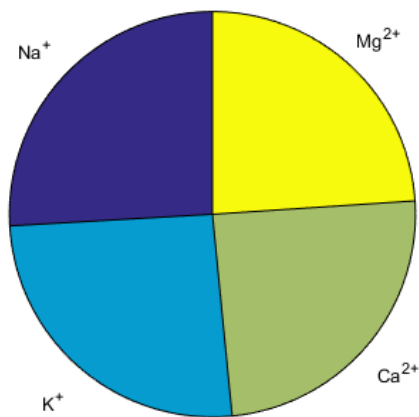
**Solute Composition in Permeate (GO,  $\phi=1.0$ )**

Fig. 6 A visual description of the relative contributions of the various solutes in the permeate

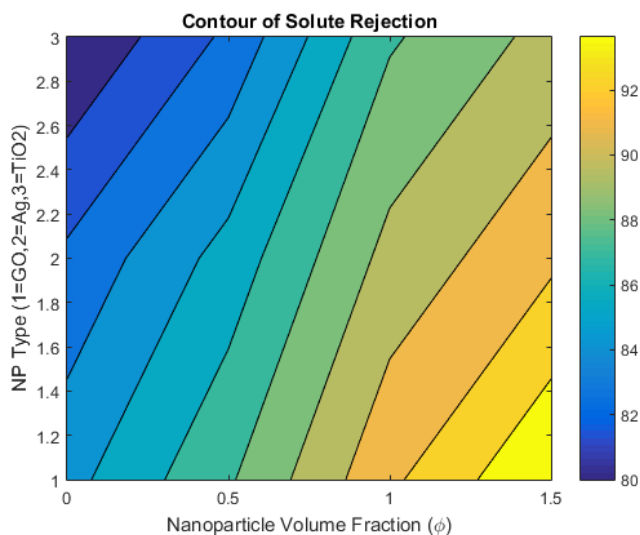


Fig. 7 The change in solute rejection as a function of both nanoparticle type and concentration

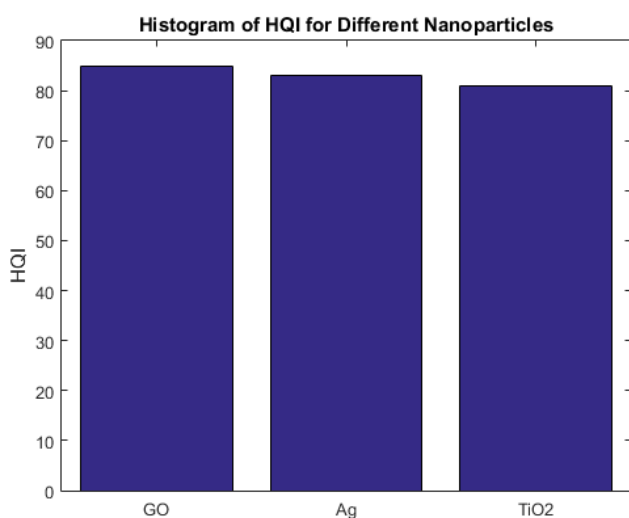


Fig. 8 A comparative hydration performance of membranes containing different nanoparticles

important factor for maintaining the physiological quality of the hydration water. Complementary to quantitative measurements of rejection of solutes and conductivity, the graphical presentation allows easy understanding of the proportional changes of the solute content.

This visualization becomes especially critical for a better understanding of the practical effects of the water treatment system on athletes. By balancing mineral content and removing excess or harmful ions, the membrane ensures that hydration water promotes electrolyte balance and overall fluid absorption. The pie chart also supports the idea of the nanoparticle incorporation improving membrane performance, thus converting the laboratory metrics into a physically intuitive water quality representation. Such transparent representation facilitates the evaluation and optimization of membrane formulations by researchers and designers for use in sports hydration applications.

Fig. 7 is a contour plot showing the variation of the solute rejection as a function of nanoparticle type and nanoparticle concentration. It can be seen that for all volume fractions, GO constantly presents the highest solute rejection while TiO<sub>2</sub> shows a slower increase. This comparison emphasizes the strong role of nanoparticle type in membrane performance, thus showing that material selection is a key parameter for the optimization of water treatment efficiency. The plot does not only allow a quick characterization of trends but also reveals a clear graphical representation of the relative effectiveness of each nanoparticle to improve the membrane selectivity. Besides showing trends, the contour plot is a useful tool in the search for best operating conditions. For use in hydration processes, it is useful for identifying an optimum type of nanoparticle and concentration for maximum solute removal with an efficient water transport. By graphically displaying these relationships, researchers can make informed choices in their membrane design to make sure that the treated water is not only clean but also physiologically acceptable to athletes. This number, in effect, converts a number of complex numerical data into a very simple and intuitive guide to help optimize hydration water quality.

Fig. 8 gives a comparative assessment of the hydration performance of membranes with different types of nanoparticles. The results show that graphene oxide (GO) is always the highest Hydration Quality Index (HQI), and close to it are silver (Ag) and titanium dioxide (TiO<sub>2</sub>). It is evident that nanoparticle selection plays an important role in the overall quality of the produced water from the membranes, as it affects the solute rejection, mineral balance, and conductivity. There is a clear, visual comparison in the figure, which makes comparing the quality of water hydration created by the respective nanoparticles easy. Fig. 8 is only a quick-reference decision-making tool for engineers and commercial users working in the sports hydration and membrane design space. This highlights the importance of considering even small variations in nanoparticle type for their impact on hydration performance which has consequences for electrolyte balance and water safety. By providing comparisons of HQI in an easy to understand format, the figure will help

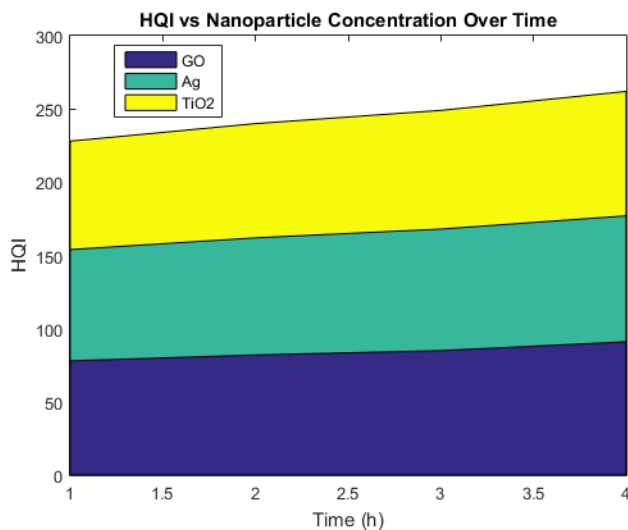


Fig. 9 The change of hydration quality with different nanoparticles over time

researchers and practitioners to identify the best nanoparticles to ensure optimal water quality for athletes for an efficient fluid replenishment and optimal physiological performance.

The region diagram of Fig. 9 shows the time development of hydration quality for membranes with different nanoparticles. Graphene oxide (GO) consistently has the highest Hydration Quality Index (HQI) at all-time points, and the trend is further improved over time. The stability and long-term efficacy of GO-modified membranes is evidenced by the behavior of the membranes, showing that their water treatment efficacy is not only effective instantly but also continuously. Silver (Ag) and titanium dioxide (TiO<sub>2</sub>) exhibit beneficial effects as well, even though their HQI is lower than that of GO due to the differences in nanoparticle properties and interactions with the membrane matrix. Apart from the absolute performance, the figure reveals also the cumulative and long-term effects of nanoparticle addition on the quality of the hydration water. Temporal stability is extremely important for sports facilities, where the water treatment plant must provide always excellent quality water for an extended period of operation. These results indicate that the choice of nanoparticle type and concentration is important to achieve an ideal hydration performance, and the GO-modified membrane seems to be a promising candidate for long-term application in the sports hydration infrastructure.

#### 4. Conclusions

The present study shows that the use of nanoparticles in membrane-based water treatment systems can greatly improve hydration quality for sports purpose. In the nanoparticles studied, graphene oxide (GO) was shown consistently to have a superior performance with regard to Hydration Quality Index (HQI), solute rejection and stability over time. Nanoparticle reinforced membranes successfully removed potentially harmful ions, while

keeping important electrolytes like magnesium and potassium for physiologically balanced water. Moreover, the modifications positively affected permeate flux and chemical stability suggesting the ability to achieve a reliable, high quality water delivery in sports facilities while not compromising throughput or long-term performance. In total, the results illustrate the strategic importance of nanotechnology for optimising hydration water beyond its conventional purification. By optimizing nanoparticle type and concentration, membranes can be modified to have selective ion rejection, stable mineral balance and fouling resistance to produce water that helps drive optimal athlete performance and recovery. These results emphasize the promise of nanoparticle-enriched membranes to revolutionize the sports hydration industry by turning sports drinks into preventive strategies for health and performance, by providing athletes with optimal quality of hydration tailored to their physiological need. The key results are:

1. Improved Solute Rejection: Nanoparticles incorporation significantly improved rejection of major ions (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>) with GO providing the most favorable result.
2. Stable Permeate Flux: Nanoparticle modification exhibited a stabilization or even slight increase in permeate flux, ensuring a consistent water supply while retaining higher quality.
3. Hydration Quality Index (HQI): GO-decorated membranes exhibited the highest HQI across all the concentrations and time, indicating the efficacy and temporal stability.
4. Better Mineral Balance: Due to the nanoparticulate enhanced membrane selectively removed the harmful ions while retaining the electrolytes needed and keeping the hydration physiologically appropriate.
5. Physicochemical Improvements: Conductivity was decreased and pH was neutralized, which indicates greater chemical stability of the treated water and safety for athletes.
6. The type of nanoparticles makes a difference: Comparison among the GO, Ag and TiO<sub>2</sub> nanoparticles showed GO > Ag > TiO<sub>2</sub> in terms of overall performance of the hydration process, indicating the importance of nanoparticle selection to achieve water quality and membrane efficiency.

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