Reducing Sugar With Fruit Juice Processing: An Emerging Market

A Framework For Membrane Filtration Technology Utilization

Troy Sharp
Process Engineer
Membrane Specialists

Enabled by the advent of pasteurization and made an economic necessity due to over production of fresh fruits, fruit juice has been a widely consumed source of hydration, energy, and nutrition for around a century. Over the 20th century, fruit juice had gone from a novelty to a crucial ingredient in any health conscious diet. During the 1990s however, it faced scrutiny as a food product that, while containing significant vitamins and minerals, contains high amounts of sugar and can lack or be low in healthy fiber present in whole fruit. This view has not stopped fruit juice from remaining a significant segment of the global beverage market, but consumer perception of juice has moved closer in assocation with soft drinks than with "health".

Consumer senitment has shifted since the 1990s toward a desire for natural, functional, and low sugar style options that are seen as more beneficial. Consumers are looking for ways to add functional nutrients to their diets without additional calories [1]. In light of these trends, producers of fruit juice have sought a way to meet that growing consumer desire [2]. Protein isolates, sugar free probiotic soft drinks, and nutraceutical concoctions seem to have entire sections dedicated to them at any given supermarket. With respect to fruit juice products, this has manifested in the form of light fruit juice drinks and a recent wave of sugar free and diet fruit beverages.

Today, the project continues as we see emerging products set to take of advantage new technologies and changes to legal frameworks around fruit juice identity that might incentivize more extensive modification of juice. Manufacturers are hoping to deliver the healthy promise of fruit juice, without the stigma of high sugar content. Numerous processes and solutions have been developed to desirably modify juices and deliver this new wave of products, each offers different advantages, challenges, and opportunities to manufacturers squeezing out the next generation of juice products.

Crossflow membrane technology in particular has provided a high degree of process leverage to manufacturers across industries for decades. Being widely utilized in clarification and concentration processes in the fruit industry, it has provided value in the form of product quality and energy cost savings. In this article we'll explore what is possible in fruit juice beyond those success stories, given the limitations of crossflow technology, with focus on the new realm of reduced sugar juice drinks.

The Promise and The Problem With Fruit Juice

In spite of its sugar content, fruit juices contain high levels of antioxidants, including essential compounds like Vitamin C, as well as polyphenols and carotenoids. These compounds are often critical for phyisological function and can promote anti-aging and anti-cancer effects [3]. From a consumer perception standpoint, natural sugar from fruit is also seen as less unhealthy than added sugar or high fructose corn syrup, to some extent [1].

However, the issue for many consumers remains that sugar level in fruit juices is simply too high to justify drinking it regularly. For example, sugar in grape juice can be up to 36 grams per 8 ounce serving, compared to a can of Coca-Cola Classic at 26 grams per 8 ounces [4].

It is partly for that reason we have seen these new juice adjacent products become mainstream recently and why the new wave is imminent.

Why Isn't There a Sugar Free "Juice"

The ideal scenario would seem to involve providing all of the benefits and taste fruit juice can offer with less or none of the sugar: true natural juice without sugar. So why hasn't that happened yet?

The issue with producing what might be considered a sugar free juice lies primarily in the way global definitions of fruit juice have been shaped historically. Fruit juice is defined by many legal bodies as the effluent resulting from the pressing of fresh fruits, which must maintain the nutrition, color, aroma, and flavor character of the fruit from which it is derived [5][6]. Legal frameworks globally vary with respect to what qualifies as "juice", what modifications can be made, what component levels need be to met, and what labeling practices are required. Under most definitions, a finished product that is intended to be sold as pure "fruit juice" cannot have less sugar in it than is present when it is extracted from the fruit. Simply put, zero sugar "juice" isn't possible, by definition, at this time.

These frameworks require producers to embrace alternative labeling such as: Flavored Fruit Juice Drink, Fruit Juice Beverage, Fruit Juice Cocktail, or even leaving mention of identity off the bottle entirely and only listing total juice content. Recent changes to the EU's framework covering fruit juice product identities and regulation, *Directive 2001/112/EC*, have provided new legal categories: Reduced Sugar Fruit Juice and Reduce Sugar Fruit Juice from Concentrate. Developments of this kind further enable the fruition of new innovations, some many years in the making, and may help provide the kind of health value consumers used to associate with fruit juice.

Approaches to Sugar Reduction

Fruit juice is a complex solution of mostly water and carbohydrates, with polysaccharides, polyphenols, minerals, organic acids, vitamins, and proteins in much smaller quantities [4][7]. These molecules and their properties give each unique fruit, and thereby fruit juice, its characteristic identity. Any technique used to alter that fingerprint can have unintended effects that take the product further away from its natural state. Removal of water via evaporation can strip volatile compounds out of the juice, too much heat can cause unwanted flavor and sensory changes, fractionation or dilution can remove desirable components that need to be replaced; all techniques have some tradeoff and associated make-up strategy.

Table 1: Sugar composition of common juices and a soft drink

Beverage	Fructose (g/L)	Glucose (g/L)	Sucrose (g/L)	Total (g/L)
Orange juice	25.6	24.0	42.5	92.2
Apple juice	60.0	27.4	13.1	100.4
Grape juice	78.3	72.4	0.4	151.2
Grapefruit juice	33.7	32.5	13.5	79.6
Pineapple juice	40.1	48.9	16.1	104.9
Coca-Cola (Original)	60.4	49.5	0.0	109.9

Juice sugar values are approximate and converted to g/L from USDA composition data using juice-specific densities [4]. Coca-Cola sugars are represented as HFCS-55 equivalent (55% fructose, 45% glucose).

Much research and development has been conducted to tune these techniques for the purpose of controlling sugar in juice products, but they resolve into two major categories: Reformulation and Modification.

Reformulation

The most direct approach to creating a sugar free fruit beverage is to formulate one using fruit juice itself, or its constiutents. Multiple juices of varying sugar content can be blended with myriad ingredients and/or diluted to create a variety of flavors and sweetness profiles offering endless possibilities.

Taking single strength juice and diluting it to reach a sugar content that is desirable, then combining that with non-sugar sweeteners, stabilizers, color, and adjusting vitamin and acid content yields a classic light Juice Beverage. You now have a product containing substantial real juice content with reduced sugar and a similar body and taste to its native juice at fewer calories per serving. Addition of fiber and polysaccharides may also be included to support any lost body while also potentially providing health benefit.

Low or no calorie style drinks take a different angle, opting to begin with water and add juice concentrates in small quantities that add little or no sugar. Formulation is then performed to bolster taste, color, and some nutritive content. The resulting beverage provides a fruit juice like experience with low to no calorie content.

The reformulation approach is relatively low com-

Table 2: Vitamin C, potassium, acid content, and total polyphenols ranges in common fruit juices

Juice	Vit C (g/L)	K (g/L)	Acid (g/L)	Polyphenols (mg/L)
Orange juice	0.30–0.60	1.8–2.5	6–12	300–600
Apple juice	0.01–0.05	0.9–1.3	3–8	200–500
Grape juice	0.02–0.06	1.0–1.5	4–10	500–1500
Grapefruit juice	0.30–0.50	1.2–1.6	8–15	400–800
Pineapple juice	0.20–0.50	0.8–1.3	5–12	200–600

Values represent typical ranges reported in USDA FoodData Central [4] and literature sources. Vitamin C and potassium values are derived from compositional databases, while acid content is expressed as titratable acidity normalized to malic acid equivalents. Polyphenol values reflect literature ranges and vary with cultivar and processing conditions [7].

plexity, boiling down to careful sensory consideration, adjustment, and product mixing to achieve the required effect. The tradeoffs of this approach manifest mainly as sensory differences from 100% juice, and, of course, marketing perception since a product cannot usually benefit from being labeled just "juice" if it is diuted and/or contains sweeteners.

Modification

Modification involves processes that directly alter or remove the sugar composition of the juice. Not all of the technologies being utilized are publicly disclosed, though a few companies have shared some details. Processes that are seen elsewhere in food processing and pharmaceuticals are likely at the forefront: adsorption, enmzymatic conversion, and membrane filtration.

One example is using immobilized enzymes to convert fruit sugars into non-digestable compounds. Glucose can be turned into gluconic acid, fructose into sorbitol, and surcose into dietary fibers, yielding a product with reduced sugar content and minimal loss of character or nutrition [8].

Selectively separating sugars via chromatography resins has been understood since the 1980s and captializes on adsorptive properties differences between glucose and fructose [9]. This could be used to reduce sugar in fruit juices without significantly altering its natural character.

Membrane filtration, specifically the nanofiltration (NF) regime coupled with diafiltration (DF), has been shown capable of passing fruit sugars to varying extents, while retaining high levels of polyphenols [10]. However, due to molecular weight overlap between sugars, vitamins, and acids, NF as technique is challenged by the loss of good components alongside sugar. At the least, it would require some additional make up strategy to compensate for any losses.

Several of these technologies in tandem, with the always availble option of reformulation, could allow for a spectrum of modification options, enabling products to be more highly tuned to consumer desires without the need for dilution or sweeteners. This class of processes is already being explored and utilized to create a new wave of sugar reduced products with potential marketing advantages over the existing reformulated approach.

Claims include 30% or greater reduction in sugar content without loss of nutritive profile, which under EU law could qualify as a clean label sugar reduced juice. Others include the presence of functional molecules and dietary fibers that offer additional benefits, but may present some ambiguity on the identity of the product. The question remains as to where some of these products will land with regard to identity, which physical processes or combinatoins thereof will require special labeling, and whether consumers will be attracted to the value propositions these products offer.

How Might Membranes Fit into Sugar Reduction Processes?

Membrane filtration, especially crossflow nanofiltration and diafiltration, sits in an interesting place in the sugar reduction conversation. It is not, at the moment, a complete solution, but as the history of membrane technology shows it is one of the most adaptable unit operations available. What might be possible with membranes given the right operating strategy? What if it were combined with the right upstream or downstream modification processes?

Coupling NF/DF with Modification

Coupling NF/DF with modification techniques essentially means changing the chemistry of the juice so that the membrane separation becomes easier and more effective. Rather than trying to directly separate sugars from compounds of similar size, which is where nanofiltration struggles, a process could use enzymatic or biochemical steps to convert sugars to more separable compounds.

Table 3: Molecular weight and nanofiltration (NF) rejection behavior of key juice components

Component	MW (Da)	Typical NF Rejection Behavior
Fructose	180	10–40%; largely permeable and difficult to remove selectively
Glucose	180	10–40%; behaves similarly to fructose
Sucrose	342	20–70%; increases with tighter membranes
Malic acid	134	5–30%; generally passes, contributes to flavor retention
Citric acid	192	5–30%; partially rejected depending on charge effects
Vitamin C	176	5–30%; mostly permeable
Oligosaccharides (FOS)	504–828	70–99%; retained depending on membrane MWCO
Dextran (low MW)	1,000–10,000	$>$90%; strongly retained
Dextran (high MW)	10,000–1,000,000	$\sim$100%; fully retained
Levan (low MW)	2,000–20,000	$>$90%; strongly retained
Levan (high MW)	20,000–1,000,000	$\sim$100%; fully retained
Phenolic acids	150–300	20–60%; partial retention, risk of flavor loss
Flavonoids	250–600	40–80%; moderately retained
Tannins (oligomeric)	500–3,000	60–95%; strongly retained
Tannins (polymeric)	3,000–20,000	$\sim$100%; fully retained

Molecular weights compiled from NIST Chemistry WebBook, PubChem, and IUPAC standard atomic weights for small molecules; carbohydrate, polysaccharide, and polyphenol ranges from food chemistry literature. Rejection ranges represent typical nanofiltration behavior in fruit juice systems and depend on membrane MWCO, charge, and operating conditions.

Sucrose to Polysaccharides

For example, converting sucrose into high molecular weight dextran or levan, creates a system where the membrane could more cleanly distinguish by molecular weight [8]. NF/DF then acts as a polishing or fractionation step, removing the remaining small sugars while retaining the modified components. This way, the membrane could work with a feed that has been intentionally engineered to match its strengths, allowing NF/DF could be more effective. This scenario could yield a lower sugar juice product with a different nutritional profile.

Monosaccharides to Oligosaccharides

A similar idea applies to oligosaccharide production. If glucose and fructose are partially converted into larger oligomers, NF could possibly be tuned so that monosaccharides pass and oligosaccharides are better retained [8]. This creates a pathway where simple sugars are reduced and partially replaced with compounds that can be positioned as prebiotic or functional ingredients.

NF/DF and Chromatography

Chromatography sits at the other end of the spectrum. It can separate sugars cleanly, but it comes with cost, complexity, and throughput limitations. A hybrid approach could yield benefit by using NF/DF to remove bulk sugar and reduce volume, or conversly using chromatography to polish the remaining sugars out of a sugar reduced NF/DF rententate stream.

Hypothetically, any or all of the approaches could be combined or arranged and could create a variety of interesting whole products or ingredients. Such a strategy could balance selectivity and scale in a way that no single technology can achieve on its own.

Key Variables in NF/DF for Sugar Reduction

As mentioned, NF/DF struggles with the fact that sugars live in roughly the same molecular weight range as many of the compounds that define juice organic acids, aromas, and some polyphenols. That overlap causes aggressive NF/DF to shed not just sugars, but desirable nutritive components as well. This creates a challenge for the technology that would requires optimized operating regimes to maximize sugar passage while retaining as much of the desirable fraction as possible.

This means NF selectivity does not offer clean separation inherently. Instead, performance could be defined by how much sugar can be removed before meaningful loss of acids, aroma, and lower molecular weight polyphenols begins to occur. This requires considering crossflow rates to control fouling effects (good and bad),

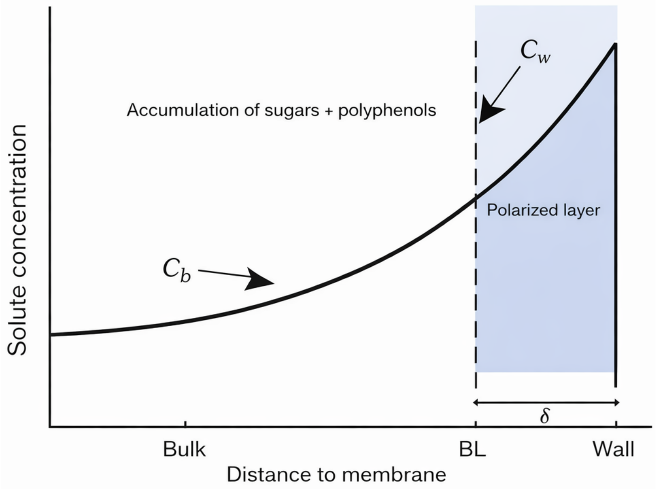

Figure 1: Idealized solute concentration profile near the membrane during nanofiltration of fruit juice. C_b represents the bulk concentration, C_w the wall concentration, and δ the boundary layer thickness where solute accumulation occurs.

appropriate pressure to avoid over fluxing, material selection, and temperature. Fortunately, controlling these variables is well understood and ongoing advancements in membrane technology and practice could improve results.

Concentration Polarization in Juice Systems

As juice flows across the membrane, sugars and polyphenols accumulate near the surface, forming a boundary layer. In sugar reduction applications, this reduces effective sugar passage and increases fouling, particularly from polyphenols. As solutes build up near the membrane, the effective driving force decreases, and a boundary layer forms. That layer causes:

- Increased local concentration and osmotic pressure
- Changes in apparent rejection of sugars
- Fouling

Managing that layer through crossflow velocity, module design, and operating conditions is one of the central challenges in applying NF to juice.

Diafiltration Strategy and Sugar Washout

Diafiltration is the primary mechanism for removing sugars in NF systems. By introducing water, permeable sugars are washed out while retained compounds. A challenge here is of course preventing over dilution that could affect product identity and flush out desirable compounds. The effectiveness of DF depends on:

- Number of diavolumes
- Timing relative to concentration
- Final product dilution constraint

An effective DF strategy requires understanding and controlling DF addition rates relative to product initial concentrations and fouling development over the course of operation.

Membrane Material and Fouling Behavior

Polyamide, the standard material used in NF membranes, tends to provide high rejection but is more susceptible to polyphenol fouling. Generally, smooth hydrophilic membrane surfaces are desirable for resistance to fouling. Over time, the fouling layer itself can begin to control separation behavior, altering both flux and the rejection of sugars. Utilizing alternate or modified membrane materials could provide advantages:

- Modified Polyamide membranes might offer some additional resistance to fouling
- Ceramic systems are interesting from a durability standpoint, but are not typically available for tight NF separations
- Mixed matrix and zwitterionic membranes may also present interesting separation characteristics that could allow further differentiation between mono- and disaccharides

Closing Thoughts

If the last century of fruit juice production was defined by preservation, standardization, and scale, the next may be defined by how deliberately we choose to shape composition. The problem of sugar reduction begins as a technical one, but it quickly becomes something broader. It raises the question of what a juice product is meant to deliver, and how much of its original composition is essential to that definition.

Consumer expectations have already begun to move in this direction. Products are no longer judged only by how closely they resemble the original fruit, but by how they fit into a wider set of goals: lower calorie intake, functional benefit, or improved metabolic response. In that context, sugar is not just something to remove, but one variable among many that can be adjusted alongside acidity, micronutrient content, and overall composition.

The approaches discussed here begin to suggest a larger design space. If sugars can be partially removed, converted, or replaced, what new compositions become practical? It is not difficult to imagine products that concentrate polyphenols beyond what is found in the original fruit, or that adjust carbohydrate profiles to target specific nutritional outcomes. At that point, the question shifts from how to make a better version of juice, to whether the goal is still to reproduce juice at all.

These possibilities also bring the role of product identity into focus. Regulatory frameworks have historically tied juice closely to its origin, but those definitions are already evolving. As new categories emerge, the boundary between juice, beverage, and functional product may continue to blur. Future products may be defined less by how closely they match the composition of fresh juice, and more by how effectively they deliver a desired set of properties.

There are still open technical questions that will shape how far this can go. How selectively can complex mixtures be modified without losing the characteristics that make them recognizable? How much separation or conversion can be applied before the result requires reformulation to remain viable? And how can these processes be arranged so that tradeoffs are managed rather than simply minimized?

Perhaps the most important unknown is whether the target itself will continue to move. As consumer preferences evolve, demand may shift away from reduced sugar versions of existing products toward entirely new categories that have not yet been clearly defined. In that case, current approaches may represent only an early step in a much larger transition.

The frontier is not a single solution, but a space of possibilities. What ultimately emerges will depend not just on any individual technology, but on how process design, product formulation, and consumer expectations come together to define what fruit-based products can be.

About Us

Membrane Specialists enables customers to be leaders in their field through customized, innovative solutions focusing on separations challenges across a wide range of industries from Food & Beverage, Pharmaceutical, Nutraceutical, Fine Chemicals, Pulp & Paper, Mining, and Water & Wastewater. Bringing over 100 years of combined experience, we partner to turn membrane technology into practical, high-performance solutions that improve efficiency, product quality, and process flexibility. We offer services from feasibility to commercialization including consultation, piloting, system design & build, implementation, and support for applications which utilize membrane technology.

About the Author

Troy Sharp leads the technical focus in the Food & Beverage industry including fruit juice processing for Membrane Specialists. His work is centered on pushing the boundaries of membrane-based separations and developing process solutions that deliver a competitive edge to manufacturing partners. Troy's goal is to drive innovation in the industry through his work taking membrane technology from concept to commercialization.

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