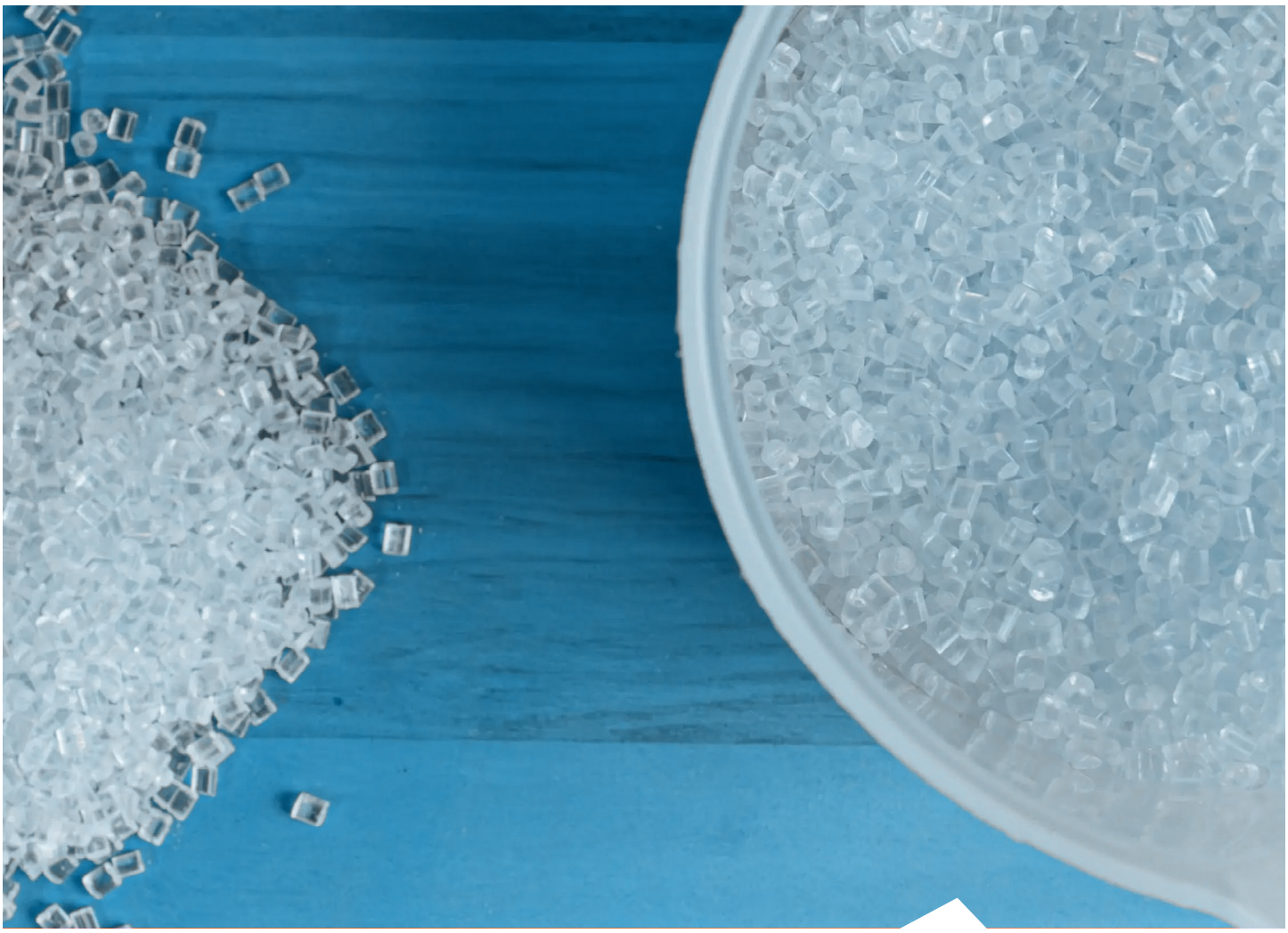
NANOLAYER

WHITEPAPER

NEW ARCHITECTURE FOR RECYCLED POLYMERS

How nanolayer coextrusion carries 30% to 50% post-consumer recycled polypropylene and polyethylene in a 50 µm film while maintaining virgin tensile performance.



EXECUTIVE SUMMARY

ONLY **9%**
GLOBAL
PLASTIC
WASTE IS
RECYCLED

A converter running a 50 µm polypropylene film line is asked to hit a recycled content target. Blending 50% post-consumer recycled (PCR) resin into the melt is simple. The result is not: the film tears at the winder, stretches unevenly on the bag line, and breaks at roughly half the stress of the virgin grade it replaced. The usual fix is to bury the recycled resin in the core under thick virgin skins, which protects performance but caps how much PCR content the film can carry.

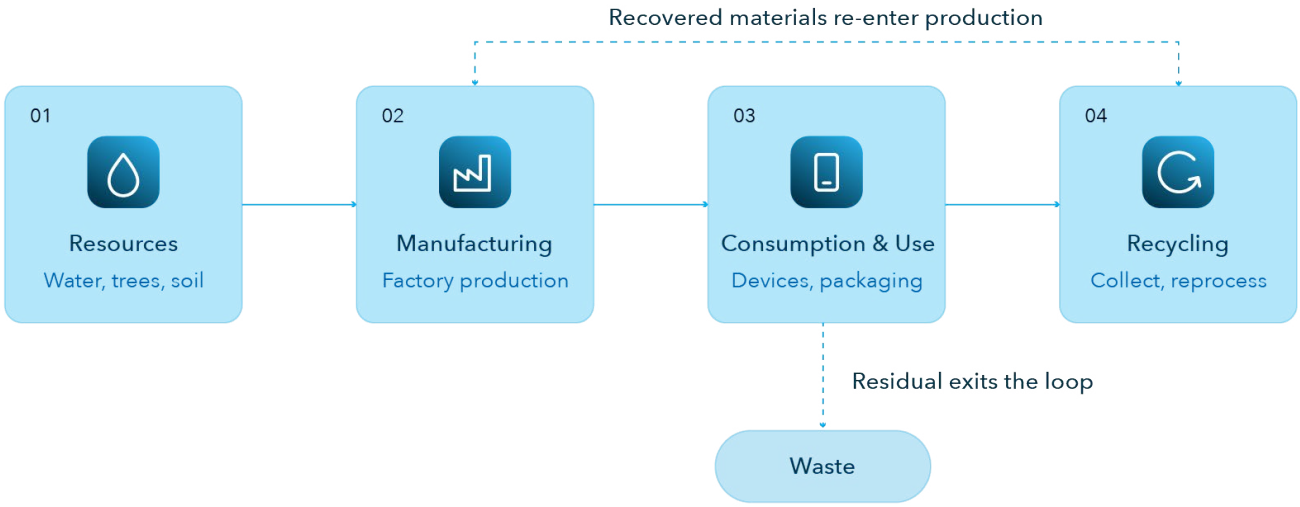
The stakes to solve this PCR performance challenge are rising. Only 9% of global plastic waste is recycled, with almost 50% landfilled, 19% incinerated and 22% mismanaged or leaked, according to the OECD Global Plastics Outlook (2022). Regulators are responding with minimum recycled content rules that apply directly to flexible and rigid packaging, and those minimums climb steeply after 2030. In addition, major consumer brand owners such as PepsiCo, Procter & Gamble, and Nestlé have made public commitments to raise the share of PCR content in their packaging and cut their use of virgin plastic. These targets send a long-term demand signal to the recycling industry, which gives collectors, sorters and reprocessors the confidence to invest in more capacity and higher-quality recycled resin. That steady pull from large buyers helps make recycling economically viable and strengthens the whole circular supply chain.

The barrier to higher PCR content isn't just the supply and quality of the recycled resin—it's how that resin is arranged inside the film. This paper presents Peak Nano data showing that distributing PCR resin across dozens of microlayers, rather than blending it or isolating it in a single core, recovers and in several cases exceeds the modulus and strength of virgin film at 30% and 50% PCR loading.

KEY FINDINGS

- **Stiffer films at 50% PCR resin.**
  33-layer PP/rPP films reached a tensile modulus of 915 MPa at 50% recycled content, versus 645 MPa for a dry blend of the same composition.
- **Strength restored.**
  Stress at break for the 50/50 33-layer PP film was 2.6 times higher than the dry blend.
- **Toughness maintained in polyethylene.**
  33-layer LDPE/rPE films at 50% PCR reached equivalent stress and strain at break compared with virgin LDPE.
- **An optimum layer count.**
  Gains peaked at 33 layers (~ 1.5 µm per layer). At 129 layers (~ 400 nm) strength generally fell back, which points to layer architecture as a design variable, not a "more is better" setting.

THE RECYCLED CONTENT MANDATE



Recycled content requirements now span both sides of the Atlantic and are written into law with dated targets. The rules most relevant to film converters are summarized below.

Jurisdiction	Requirement	Timing
European Union (PPWR)	Minimum recycled content: 10% for contact-sensitive non-PET plastic packaging, 35% for other plastic packaging	2030 (rising to 25% and 65% in 2040)
California (AB 793)	Postconsumer recycled content in plastic beverage containers: 15%, 25%, then 50%	2022, 2025, 2030
U.S. Department of the Interior	Phase out single-use plastic products on Interior-managed lands (Order 3407)	By 2032

Sources: *FoodNavigator PPWR timeline (2026); CalRecycle; U.S. Department of the Interior. See Sources for links.*

The EU Packaging and Packaging Waste Regulation (PPWR) sets its first recycled content thresholds for January 1, 2030 (FoodNavigator, 2026). California already enforces aggregate PCR minimums on beverage containers, with penalties for shortfalls (CalRecycle). In the US, the Department of the Interior committed in 2022 to phase out single-use plastics on the lands it manages by 2032. Each of these raises the volume of PCR that converters must absorb without losing film performance. The deadlines are closer than they look. A new packaging structure typically takes two to three years to move from material selection through line trials, shelf-life testing and regulatory sign-off before it reaches the market. With the EU thresholds just over three years away, converters and brand owners that have not started qualifying higher-PCR films are already short on time.

WHY RECYCLED POLYOLEFINS LOSE PERFORMANCE

Post-consumer polyolefin streams are rarely a single, clean grade. They mix resins with different molecular weights and melt flows, carry residual additives and pigments, and can contain small amounts of other polymers from multilayer packaging. EVOH carried over from barrier films is one example the industry has identified as degrading recycled material properties (Plastics Recyclers Europe announces new findings for PE film recycling). When this material is melt blended into virgin resin, the impurities and weak phases are distributed throughout the film, and the weakest regions set the film's failure point.

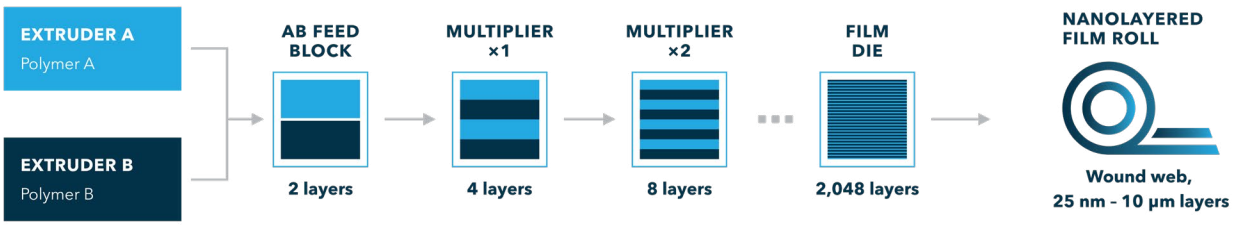
The established workaround is to keep PCR resin away from the surfaces. Traditional layered films place recycled resin in a core and cover it with thick virgin cap layers that carry the mechanical load and protect sealing and print surfaces. Approaches built around thick protective skins tend to limit how much PCR the whole film can carry, because the skins themselves must stay virgin.

MICROLAYER AND NANOLAYER COEXTRUSION

Layer multiplying coextrusion is an established, scalable melt process. It can be traced to the interfacial surface generator patented by Harder at Dow (1965), which repeatedly splits, stacks and recombines polymer streams. Modern feedblocks use rheologically corrected flow channels to build films with a desired number of layers, from 2 to more than 1,000, and the literature documents property gains across barrier, mechanical, optical and dielectric performance (Langhe and Ponting, Elsevier, 2016).

The technique is commercial across several markets, including multilayer optical films and microlayer gas barrier membranes for air-cushioned footwear. Traditional packaging films use 3, 5 or up to 11 layers. Micro- and nanolayer films use 32 to more than 4,000 layers.

Peak Nano's process has produced films and sheets ranging from 2 to 4,000 +layers, with individual layers as thin as 25 nm. Development follows two steps: formulating rheologically matched material pairs, then designing the layer architecture (film width, number of layers, total thickness and relative composition). The process has been applied to a wide range of commercial and developmental polymers, including polyolefins (PE, PP, COC), nylons, PET, EVOH, styrenics, acrylics, polycarbonates, fluoropolymers, elastomers, TPUs, LCPs, polysulfones, cellulose and biopolymers.



Number of layers = $2^{(n+1)}$ where n = number of multipliers

Example: 10 multipliers = 2,048 layers

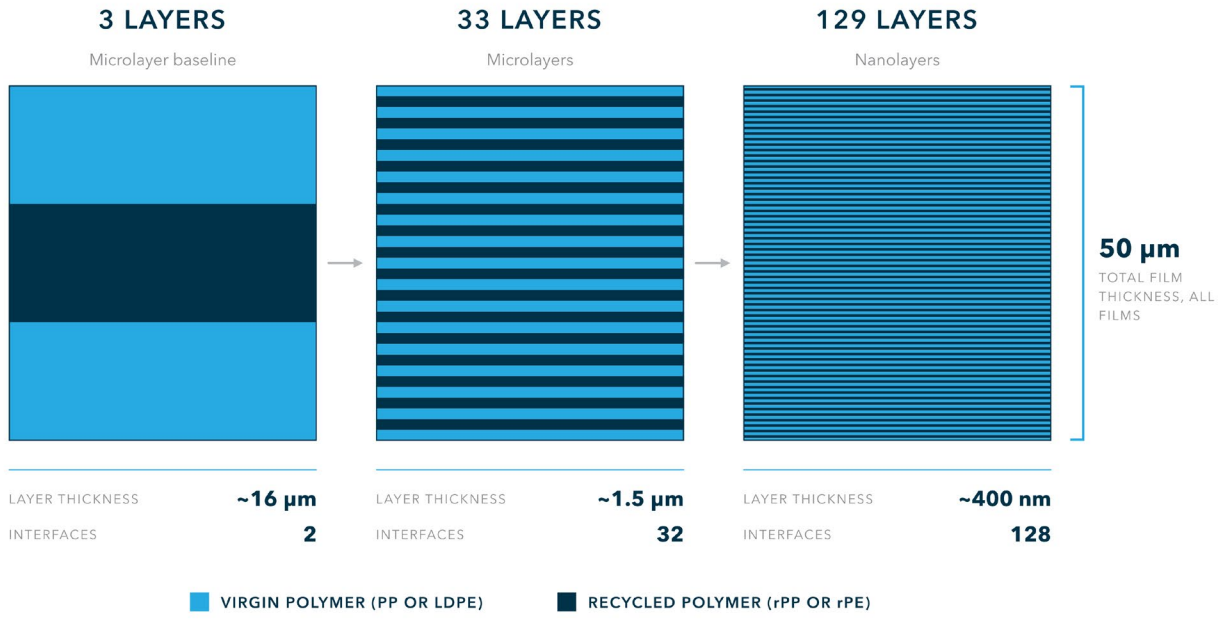
STUDY DESIGN

To understand how PCR content affects final film performance, we ran experiments with PCR loadings of up to 50% and compared three incorporation methods: dry blending, melt blending, and nanolayering. Two material systems were tested, each at a fixed total film thickness of 50 µm, produced by flat cast coextrusion. The goal was to process films with more than 30% recycled content while keeping the mechanical properties of neat virgin film.

Variable	Polypropylene system	Polyethylene system
Materials	Virgin PP Recycled PP (rPP, sourced from St. Joseph's Plastics)	Virgin LDPE Recycled PE (rPE, sourced from Green Industries)
Virgin/recycled ratio	70/30 and 50/50	50/50
Layer counts	3, 33 and 129	3, 33 and 129
Layer thickness	~16 µm (3-layer) down to ~400 nm (129-layer)	~16 µm (3-layer) down to ~400 nm (129-layer)
Controls	100% PP, 100% rPP, melt blend and dry blend at target composition	100% LDPE, 100% rPE, dry blend at target composition

Tensile testing used strip specimens 2.5 cm wide and 15.2 cm long with a 5.0 cm gauge length, pulled at 508 mm/min on a single-column Instron frame. Reported properties included Young's modulus and 2% secant modulus, strain at break, stress at break, load at break and area under the stress-strain curve.

Film Layering Structure



RESULTS: POLYPROPYLENE

Every nanolayered PP film was stiffer than the single-layer controls, independent of overall recycled content. The 33-layer structure produced the highest modulus in each series, and it delivered the largest strength gain at 50% PCR resin.

At 30% rPP resin content, the 33-layer film had the highest modulus (945 MPa) and surpassed the melt and dry blend films at the same composition. Structuring the film into layers induced more strain hardening through the architecture. Stress at break also showed improvements over the blended samples and were comparable to the virgin control. Moving to 129 layers did not provide further improvement in properties. Higher modulus at equal thickness supports downgauging and improves film handling on converting lines.

At 50% PCR resin inclusion, the 33-layer film was also the highest modulus at 915 MPa versus 645 MPa for the dry blend, a gain of roughly 40%, and again showing a strain hardening behavior. The melt blend of the 50/50 composition was unable to be processed and therefore was not included in the data. Stress at break started low for the rPP (6.8 MPa) and rose to 10.1 MPa in the dry blend and 12.1 MPa in the 3-layer film. The 33-layer system achieved the highest stress, and was even higher than the virgin control. Adding additional layers actually showed a decrease in stress at break behavior.

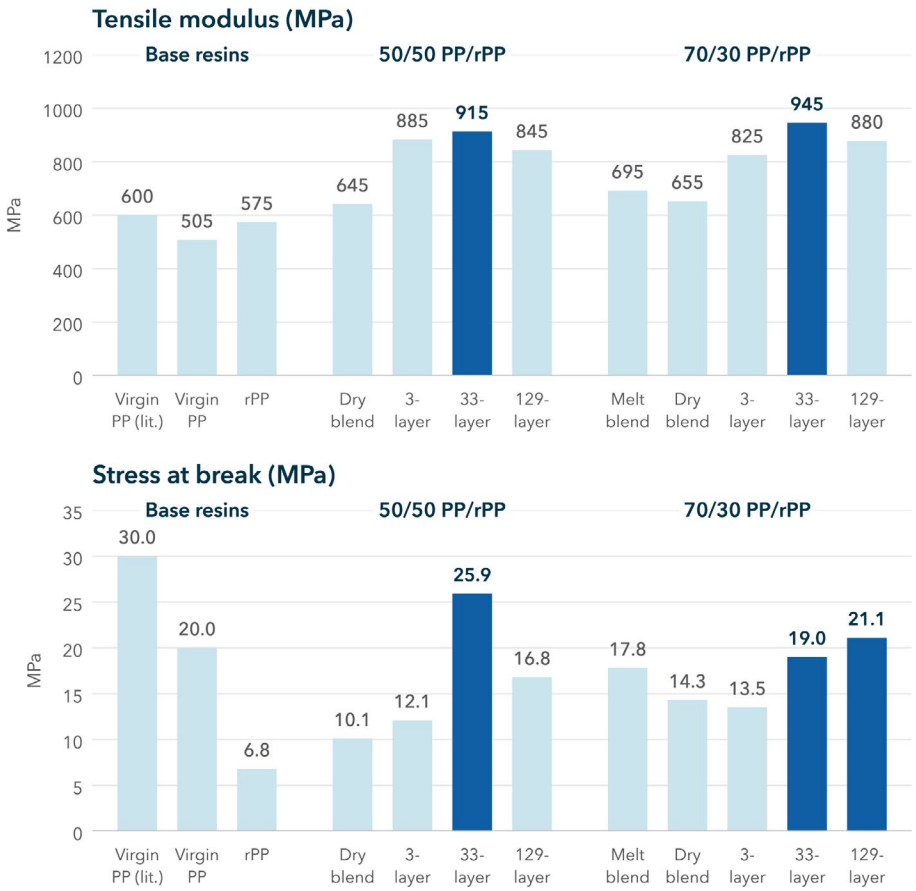


Figure 1. *Tensile modulus and stress at break for 50 µm PP/rPP films. Dark bars mark the strongest layered structure in each series. Data: Peak Nano internal testing.*

RESULTS: POLYETHYLENE

Layering rPE with virgin LDPE maintained the toughness of the neat polymer with no change to modulus. The 33-layer film delivered the clearest gain.

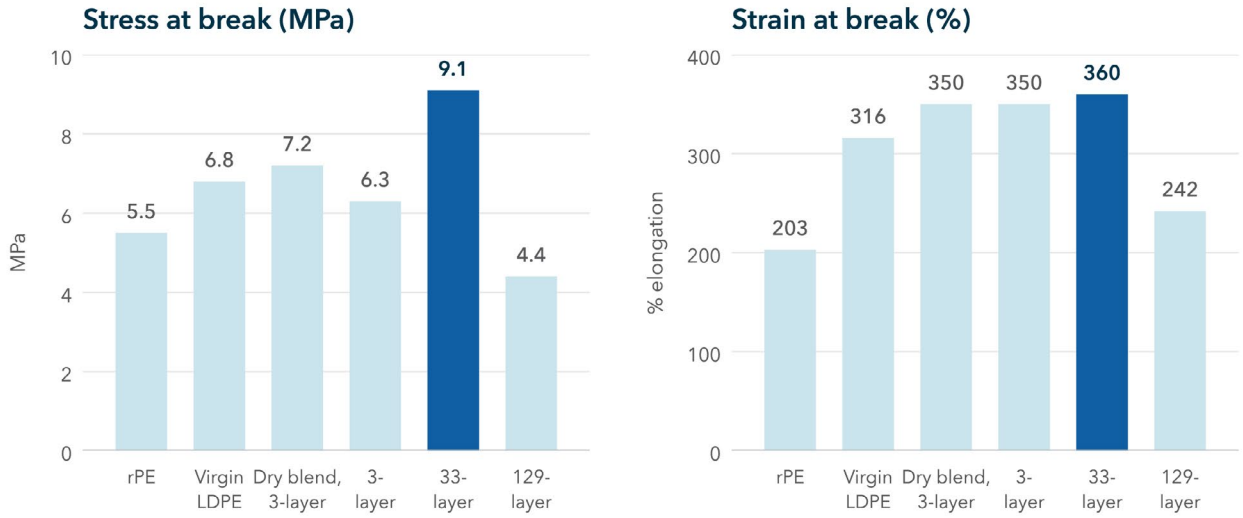


Figure 2. *Stress and strain at break for 50 µm LDPE/rPE films at 50% recycled content. Data: Peak Nano internal testing.*

Layering produced a similar benefit in polyethylene. The 33 layer LDPE/rPE film broke at a stress about 34% higher than virgin LDPE and about 65% higher than the rPE. Stress at break shows how much load a film can carry before it fails, which matters for puncture resistance, seal strength and the option to downgauge. Elongation shows how far the film can stretch and absorb energy before it splits, which governs how it handles drops, impacts and stretching during packing and handling. Because the layered film improved on both, it is tougher overall, resulting in the ability to incorporatemore recycled content without losing durability. Mechanical performance gain was smaller than in polypropylene layered system, mostly due to less variation in the virgin LDPE and rPE materials examined in this system as compared to the virgin PP and rPP resins.

WHY LAYER COUNT MATTERS

Several interrelated mechanisms are consistent with these results. Continuous virgin layers can carry load across defects and impurities that are confined within adjacent recycled layers, rather than dispersed through the whole film as they are in a blend. The large interfacial area of a multilayered film may also promote nucleation and higher crystallinity in the virgin PP layers, which is consistent with the modulus gains observed. Both effects are documented for layered polymer systems in the broader literature (Langhe and Ponting, 2016).

The drop in strength at 129 layers in most series shows the benefit is not monotonic. At roughly 400 nm, layers approach the scale of the defects and contaminants in the recycled stream, and interfacial effects or layer breakup may begin to take over. The practical takeaway for converters is that layer count and thickness should be tuned for each PCR source, which is made possible by the feed block design.

FROM LAB TO PRODUCTION SCALE

A layered film is only relevant if it can be made at the volume required for its application. Peak Nano has demonstrated this through its NanoPlex capacitor film program, where films are wound from long continuous rolls and must meet tight thickness tolerances. The same layer multiplying process used in this study runs on dedicated development and production lines.



Production parameter	Development lines	Production line
Maximum production rate	1 to 50 lb/hr	50 to 300 lb/hr
Film width	12 to 36 in	32 to 36 in
Film thickness	4 to 300 μm	8 to 300 μm
Output	300 to 3,600 ft²/hr	8,000 to 48,000 ft²/hr

Peak Nano layered film production capability (capacitor film configuration). Line speeds reach 200 ft/min.

Nanolayered capacitor films from this capability have been validated by U.S. Government and commercial partners in functioning devices ranging from small (50 μF) to large (multiple kJ) capacitors. For packaging, the development and scale up has proven to run at industrially relevant rates, speeds and widths.

PATH FORWARD

Since both systems in this study pair a virgin polymer with its own recycled counterpart (PP with rPP, PE with rPE), the finished films remain single-polymer structures. That keeps them compatible with existing polyolefin recycling streams, which mixed-material laminates are not. Peak Nano holds U.S. Patent 11,945,196 B2, granted in 2024, covering flat-cast multilayer films and sheets that combine virgin and post-consumer recycled LDPE or PP in alternating layers 100 nm to 3 µm thick.

Recycled content minimums will tighten through 2040, and every percentage point of PCR resin that a film can carry without a performance penalty reduces both compliance risk and virgin resin demand. Next steps for this work include end-of-life improvements and the effect of layering on biodegradable and compostable formulations, where weak mechanical properties are often the barrier to adoption.

Test your PCR stream in a layered film

Peak Nano can produce layered film samples from your virgin and recycled resins through its Films as a Service (FaaS) program, typically in 1 to 3 weeks. Contact the Peak Nano films team at peaknano.com to discuss your recycled content targets.

FREQUENTLY ASKED QUESTIONS

1. **How much PCR resin can a nanolayered polyolefin film carry?**
   In this study, PP and LDPE films carried 30% and 50% post-consumer recycled content at 50 µm thickness. At 50% PCR resin, the best layered structures matched or exceeded virgin film in modulus and stress at break.

2. **Why not just blend the recycled resin?**
   Blending spreads impurities and weaker phases through the entire film. In this study, a 50/50 PP/rPP dry blend broke at ~10 MPa, while the same composition in 32 layers broke at ~26 MPa.

3. **Are more layers always better?**
   No. Performance peaked at 33 layers (~1.5 µm per layer) and generally declined at 129 layers (~400 nm). The optimum likely depends on the recycled stream, so layer architecture should be tuned for each application.

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