

Design of a Food Packaging Sustainability Framework

An integrative, life-cycle-based framework for balanced packaging design decisions

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Abstract

Thus food packaging decisions must consider three objectives at the same time: reducing the environmental impact, maintaining the quality and safety of foods and providing economic and social benefits. These goals are often in conflict with each other, and are rarely achieved by the most common approach today of substituting one packaging material for another, supposedly greener material. Material substitution alone rarely resolves the real trade-offs. It can shift an impact from one life cycle stage to another, rather than avoiding it. This paper proposes a structured Food Packaging Sustainability Design Framework (FPSDF) to assist the packaging developers, food manufacturers and regulators in realizing balanced and well-evidenced design decisions. The framework emerged from a structured reading of the recent literature and the current European regulatory regime. It breaks down the decision into five interrelated levels: context and requirements, sustainability goals, design levers, evaluation and trade-off analysis, and decision and validation. They are all underpinned by four principles: life-cycle thinking, do-no-significant-harm, transparency and stakeholder co-design. Each of the three dimensions of sustainability is translated into measurable objectives, a set of levers that a designer can act on and a panel of performance indicators. The framework combines life-cycle assessment with multi-criteria decision analysis to make competing aims visible and manageable and explicitly addresses the food loss that packaging can prevent or cause. A worked example with a chilled meat tray demonstrates how the method distinguishes between options that appear similar when screening on a single issue. The FPSDF is proposed as a flexible scaffold rather than a rigid checklist and the assumptions, limitations and validation needs are discussed.

Keywords: 1. Food packaging 2. Sustainability 3. Life-cycle assessment 4. Multi-criteria decision analysis, 5. Trade-off analysis

1 Introduction

There are few parts of the food system so easy to take for granted as packaging. Its obvious job is to hold the product but it does a lot more than that. Good packaging protects food from damage,

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chemical change and micro-biological spoilage. "It improves quality and extends the useful life of a product. It delivers the information that shoppers and supply-chain partners rely on and makes possible the efficient movement and processing of goods.¹ None of this is decorative. If packaging were to fail at these tasks, a far larger share of the energy, water, and land already spent on growing and processing food would be thrown away with the spoiled product. Packaging is also, however, one of the most criticised parts of that same system. It is produced in vast quantities, much of it is used once and discarded, and it shows up plainly in bins, on streets, and in rivers and oceans.

The numbers behind the concern are large. In industrialised economies a sizeable proportion of all plastic and paper produced ends up as packaging, and the volume of packaging waste in the European Union has grown by more than a fifth in ten years, with further growth expected if nothing is done.^{5,6} Worries about plastic escaping into nature, the build-up of marine litter, and the long life of fossil-based polymers have triggered new rules, a rush to replace ordinary materials with bio-based or recyclable ones, and rising shopper interest in packaging that looks environmentally friendly.^{2,4} The trouble is that much of this response has been narrow. It treats sustainability as though it came down to a single question: which material should we use?³ That question is appealing because it is simple. It is also misleading, because a material that scores well on one measure, such as how renewable it is, can score badly on others, including barrier performance, whether local facilities can really recycle it, and price.^{15,19}

The deeper difficulty is that sustainability in food packaging has several dimensions and is full of genuine trade-offs. Take a package and make it lighter. Its production impact drops, but it may now protect the food less well, so more of that food is lost. This matters because the footprint of the food itself usually dwarfs the footprint of its packaging. A package that gives way too soon can therefore do more environmental harm than a heavier one, even when the lighter package looks like the greener choice on paper.^{7,32} Life-cycle assessment (LCA) keeps making the same point. The impact of a packaging choice on the entire system depends on the specific food, its mode of transportation, the human activity with the food, and the fate of the package at the end of its life in that specific location.^{8,27} what works well in one setting can go wrong in another.

There are three reasons that this is a good time to be more systematic. The first is regulation. Rules are moving away from specifying individual materials toward specifying the system-wide performance requirements. Europe's Packaging and Packaging Waste Regulation (PPWR) entered into force in February 2025 and is applicable from August 2026. The PPWR sets common obligations for recyclability, recycled content, packaging reduction, reuse and substances of concern for all products sold on the EU market.⁵ Other regions are moving in similar ways towards

targets for extended producer responsibility and circular economy⁴. The second is the tool box. Designers now have far more to work with, from bio-based and biodegradable polymers and fibre formats to reuse systems and active or intelligent packaging that lengthens shelf life and cuts waste.^{2,10,21} The third is measurement. LCA and multi-criteria decision analysis (MCDA) have matured enough to sit inside everyday design work instead of being saved for an audit after the fact.^{8,25}

What is still missing is the thing that ties these threads together. There is no widely used scaffold that carries a team from a sustainability ambition to a specific, defensible design while keeping every dimension of sustainability in view and in balance. Earlier studies have set out conceptual frameworks naming the dimensions of sustainable food packaging,³ and the circular-economy literature has explained in detail how packaging feeds closed material loops.^{24,25} Far less work turns those ideas into a working design-and-evaluation routine that a practitioner can apply to one product in one market.

This paper attempts to fill that gap. The goal is a Food Packaging Sustainability Design Framework (FPSDF) that does four things: it names the dimensions of food packaging sustainability and the objectives attached to each; it names the levers a designer can pull to reach those objectives; it marries LCA and MCDA so trade-offs are declared openly and food-waste effects are not silently dropped; and it puts the resulting choice inside a loop that tests and revises it. The rest of the paper runs as follows. Section 2 explains how the framework was built. Section 3 lays out its conceptual basis and the three dimensions. Section 4 describes the architecture and its five layers. Section 5 puts the framework to work through indicators and a worked MCDA example. Section 6 weighs barriers, enablers, and research needs, and Section 7 concludes.

2 Framework development method

The framework grew out of a three-stage, design-science process that paired a structured reading of the literature with repeated rounds of conceptual modelling. The intent was not an exhaustive systematic review. It was to gather a sound evidence base and then draw design principles from it, following the way conceptual frameworks are usually built in packaging and circular-economy research.^{3,12}

The first stage scoped the literature across four overlapping themes: how sustainable food packaging is defined and framed; the materials and technologies in play, including bio-based polymers and active and intelligent systems; the methods used to judge environmental performance, mainly LCA and how it handles packaging-related food waste; and the surrounding

regulatory and market context, including what consumers think and what they will pay. Priority went to peer-reviewed reviews and primary studies from roughly 2022 to 2026, with a few older foundational papers and the relevant regulatory texts added. Open-access sources and official documents were favoured so the work can be retraced.

In the second stage the recurring ideas were extracted and classified. Overall, the literature agrees on three interpretations of food packaging sustainability even when a single paper only emphasizes one: environmental conservation, food protection and safety, and social and economic value, the interpretation was confirmed^{3,24}. It also confirmed that four points of intervention come up again and again, material choice, structural design, added function and circularity design and that LCA and MCDA are the methods most often used to evaluate them^{8,25}.

In the third phase we organized these groups into a layered decision architecture. The sequence of layers is a deliberate path: reading the context; setting objectives and choosing levers; weighing trade-offs and checking the outcome, with feedback loops that make clear how real packaging design loops back rather than running straight through. The architecture was then refined for internal consistency, and tested against the worked example in Section 5 to ensure that it provides recommendations that actually distinguish between options.

3 Conceptual foundations: three dimensions of food packaging sustainability

Sustainability is often pictured as three pillars: environment, economy, and society. For food packaging that picture needs adjusting, because packaging has a job the generic model does not capture, which is to protect a perishable product on which health can depend. Reading across the literature points to three connected dimensions through which packaging contributes to sustainability, shown in Figure 1: environmental conservation, food protection and safety, and social and economic value.³ Look at any one of them alone and you get exactly the narrow, material-first thinking criticised above. The point of the framework is to keep all three together.

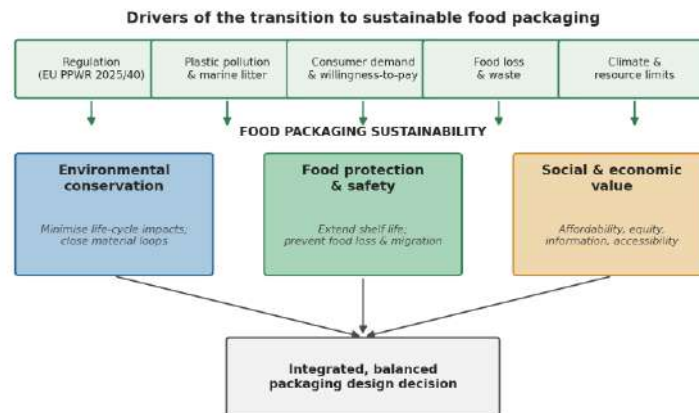


Figure 1. The drivers of the transition to sustainable food packaging and the three interdependent dimensions to balance in any design decision.

3.1 Environmental conservation

The environmental dimension is about the load packaging places on natural systems over its whole life, from pulling out raw materials through conversion, distribution, and use to whatever happens at the end, and about how well materials stay in use rather than being discarded. Fossil plastics still dominate food packaging for good reason: they're flexible, they make great barriers, they're light and they're cheap. The downside is that they use finite feedstock's and they stick around in the environment. That's the crux of the problem^{15,31}. "The way to reduce environmental load is to work several levers at the same time: use less material and energy, switch to renewable or recycled inputs, design the package so it can be recycled or composted, and build systems that allow reuse ^{24,25}.

Only the feedstock determines nothing. LCA work shows that for some products the packaging stage really is the biggest contributor to certain impacts, but for foods which are highly perishable or expensive to produce, the protection packaging gives can more than pay for its own footprint by stopping the food from being wasted^{26,27}. Food-packaging LCAs frequently identify shelf-life extension as one of the attributes that has the greatest influence on the overall impact of the system, especially for high-impact foods such as meat, dairy, and fresh produce.⁷ Therefore a sound assessment must consider the whole life cycle and, where possible, compare the performance of the package with the food it protects, rather than rating the package by itself.

3.2 Food protection and safety

The second dimension is packaging in the first instance. It is about getting the food to the consumer safely, soundly and of acceptable quality. It provides protection against oxygen, moisture, light and

loss of aroma, as well as against physical damage and against microbial and chemical contamination. It also concerns the safety of the package itself, as chemicals can migrate from packaging into the food. Whether recycled and novel food-contact materials are safe is a live question for both regulators and researchers^{9,5}. This dimension is developed by active and intelligent packaging. Active systems work on the product or the air around the product with antimicrobials, oxygen scavengers or moisture controllers to retard spoilage. Intelligent systems are equipped with indicators and sensors to read freshness and relay that reading along the chain^{20,21,22}.

This is the dimension where the environmental and economic aspects come together most clearly. It is a powerful lever for sustainability to prevent food from being wasted, avoiding the upstream burden of having produced it in the first place, even if it adds a little to the package's own footprint^{7,29}. That is the trade-off that material substitution tends to obscure and it is a major reason the framework requires packaging assessment to be tied to food waste outcomes.

3.3 Social and economic value

The third dimension is the value packaging brings to people, and to the companies and communities that create it and consume it. It considers affordability and access, honest and legible information about what is inside and how to handle and dispose of it, sensible portioning and convenience, and the part packaging plays in keeping supply chains fair and resilient. What consumers think matters, but the evidence is mixed. People say they would pay more for packaging they see as sustainable, but not for options they see as unsustainable or cannot judge. What they think is sustainable often does not match the real impact^{11,12}. Surveys show the swings in premium shoppers will accept widely with region, income and age, and that price sensitivity keeps it in check^{13,14}. The lesson is that communication has to be clear and verifiable, and that a design's green claims have to survive scrutiny.

The economic side is equally important. No matter how good they look environmentally, bio-based and biodegradable options are often more expensive and sometimes perform worse, holding back their uptake^{19,31}. More and more tools like extended producer responsibility and eco-modulated fees are being employed to push end-of-life costs back to producers and to incentivize packaging that is easier to recycle or reuse, which alters the economics of a design^{4,5}. Any framework that leaves cost and manufacturability out of the equation will produce answers that look beautiful on the page and are impossible in the marketplace.

3.4 Interdependence and the risk of burden-shifting

These three dimensions are not separate boxes to be adjusted one after the other. They are connected, and a gain in one can mean a loss in another. Reduce the size of a package and its

material impact goes down, but its shorter protection might increase food loss, harming the very environmental and economic outcomes the change was supposed to help. Switch to a compostable film and the story sounds good, yet where no local composting route exists the film is landfilled or burned, and it may foul a fibre or plastic recycling stream on the way.¹⁵ Active agents that extend shelf life bring a production impact of their own and can make recycling harder. Recycled-content rules improve circularity but raise food-contact safety questions that then have to be settled.⁹ This is burden-shifting: an apparent win that only moves the impact to another stage, another dimension, or another actor. It is the standard way single-issue design fails. The layered structure of the framework, together with its do-no-significant-harm principle, is built to bring these links into the open before a choice is locked in, not after it has shipped. Keeping the three dimensions together is not a matter of taste. It is what stops good intentions from adding up to a worse result.^{3,7}

4 The Food Packaging Sustainability Design Framework

The FPSDF turns the three dimensions into a working decision process. It is laid out as five connected layers, shown in Figure 2, and held together by four principles that cut across all of them. The layers run in an order that mirrors a sensible design progression, but the process is openly iterative: what is learned in a later layer can, and often should, change an earlier choice.

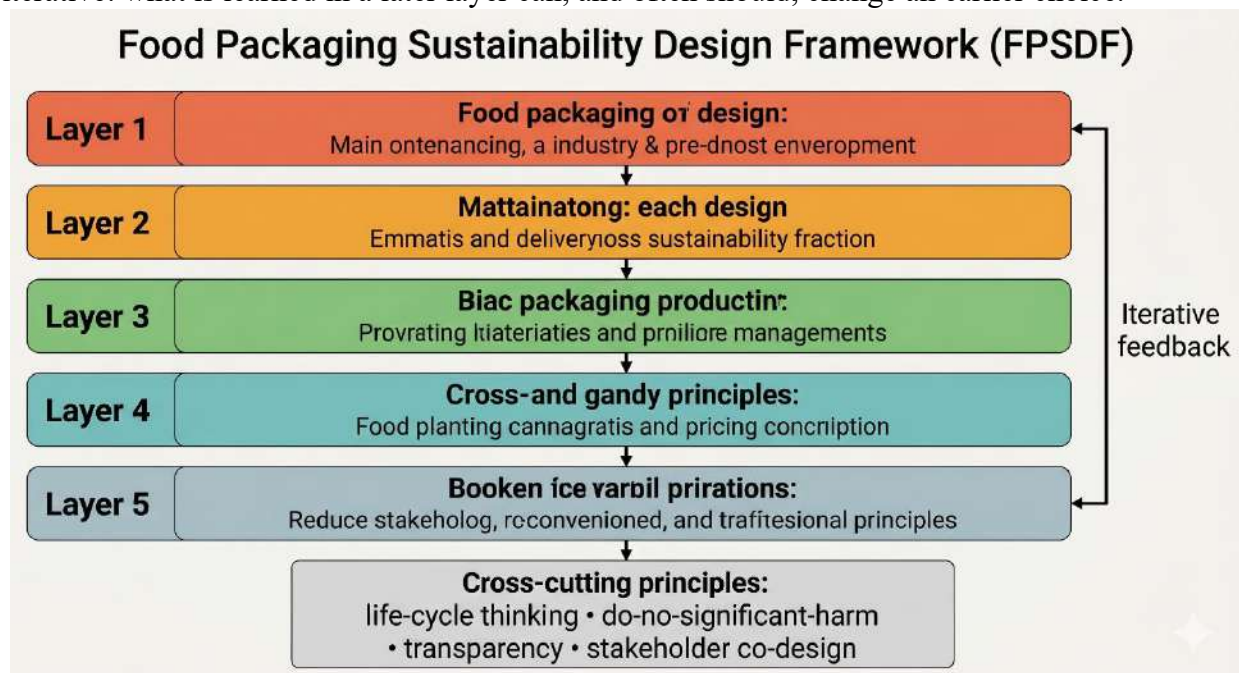


Figure 2. *Architecture of the Food Packaging Sustainability Design Framework, comprising five interacting layers governed by four cross-cutting principles, with an iterative feedback loop from validation back to context.*

4.1 Cross-cutting principles

Four principles apply everywhere in the framework. The first, **life-cycle thinking**, asks that each decision be judged by its effects on the whole system, food included, not by one stage or by the package alone.^{7,8} The second, **do-no-significant-harm**, asks that a gain on one dimension, say moving to a compostable film, not cause an outsized loss on another, such as losing recyclability in the local system or weakening food safety.⁹ The third transparency, is to record assumptions, data and uncertainties so that any claim can be verified and defended, which speaks directly to the gap between what appears sustainable and what is^{11,12}. The fourth is stakeholder co-design and involves packaging developers, food technologists, waste-management operators, retailers and, where possible, consumers, as the performance of a packaging system depends upon actors and infrastructure not controlled by the designer²⁴.

4.2 Layer 1 Context and requirements

The first layer is the design space. It's the food and how it spoils (oxidation, microbial growth, moisture exchange, physical damage), the shelf life required, the conditions along the supply chain (temperature, distance, handling), the target markets and the rules that bind them, and most tellingly, the end-of-life infrastructure that consumers in those markets can actually access. That last one is often what makes the difference. A recyclable or compostable package is useless in practice unless there is a facility nearby to collect and process that material^{5,15}. For example, the basis for all subsequent work is a well-defined functional unit, e.g. "deliver one kilogram of chilled product to the consumer with a specified shelf life and an acceptable loss rate". Thus the comparison does not degenerate into a battle of package against package from which the food is lost sight.

4.3 Layer 2 Sustainability objectives

The second layer converts the three dimensions into specific objectives, weighted to fit the context set in Layer 1. A long-haul ambient product might be driven mainly by cutting material and being recyclable. A highly perishable chilled product might be driven mainly by extending shelf life to head off food loss. Stating that weighting openly at this point, rather than letting it slip in through the choice of material, is what lets the framework handle trade-offs in plain sight. Table 1 lays each

dimension against representative objectives, the levers that serve them, and example indicators, giving the menu from which context-specific objectives are chosen.

Table 1. Mapping of the three sustainability dimensions to objectives, design levers, and example indicators.

Dimension	Representative objectives	Activable design levers	Example indicators
Environmental conservation	Minimise life-cycle impact; maximise circularity; use renewable/recycled inputs	Mass reduction; recyclable mono-materials; recycled or bio-based feedstock; reuse systems	kg CO ₂ -eq per functional unit; recycled content (%); recyclability (%)
Food protection & safety	Achieve required shelf life; prevent contamination and migration; reduce food loss	Barrier optimisation; active agents; intelligent indicators; format and seal design	Shelf-life (days); spoilage/loss rate (%); migration vs. limits
Social & economic value	Ensure affordability; provide clear information; support fair, resilient chains	Cost-efficient design; clear labelling and disposal guidance; accessible formats	Total cost per unit; label clarity score; EPR fee modulation

4.4 Layer 3 Design levers

The third layer is where concepts get built, by mixing choices from four lever families: material selection, structure and format, active and intelligent functions, and circularity design. The best concepts come from combinations, material by format by function by end-of-life route, rather than from a lone material swap, because these levers act on one another.

Material selection. The range runs from conventional fossil plastics through fibre materials and recycled-content plastics to a widening set of bio-based and biodegradable polymers. Of the last group, polylactic acid (PLA) gives mechanical behaviour close to that of common fossil plastics and is already one of the most produced bioplastics, though its barrier and heat performance usually have to be improved.^{16,17} Polyhydroxyalkanoates (PHAs) come from renewable sources, break down well including in compost, and can be grown on agri-food waste, but cost and limited production capacity still hold them back.^{16,18} Starch- and cellulose-based films and protein films bring renewability and, in several cases, compostability, yet they generally need blending or reinforcing before they can meet barrier and strength targets.^{15,31} Table 2 sets representative

materials side by side, and Figure 4 shows how the options trade off across several criteria. No single material leads on every axis, which is exactly why a structured trade-off step is needed.

Table 2. Comparison of representative food-packaging materials. Properties are indicative and depend on grade, processing, and additives.

Material	Feedstock	Key strengths	Principal limitations	Typical end-of-life
PET	Fossil	Excellent barrier; strong; established recycling	Fossil-derived; persistent; downcycling common	Mechanical recycling
Polypropylene	Fossil	Versatile; low cost; heat-stable	Fossil-derived; lower recycling rates	Mechanical recycling
Paper / board	Renewable	Renewable; widely recycled; good public perception	Moisture-sensitive; coatings can impair recycling	Fibre recycling
PLA	Renewable	Stiff; clear; industrially scaled bioplastic	Limited barrier/heat resistance; needs dedicated processing	Industrial composting
PHA	Renewable	Biodegradable incl. marine; from waste feedstocks	Higher cost; limited scale; variable properties	Composting / biodegradation
Starch blends	Renewable	Low cost; compostable; abundant	Poor moisture barrier; needs blending	Composting
Cellulose films	Renewable	Renewable; good clarity; compostable grades	Moisture-sensitive; cost	Composting / fibre recovery

Structure and format. Whatever the material, designers can trim mass and over-packaging, drop unnecessary layers, shift from multi-material laminates to recyclable single-material structures, and pick a format (flexible or rigid, single- or multi-serve, refillable or single-use) that fits the product and the market. Reducing packaging and designing it for recycling are no longer voluntary nice-to-haves; they are written into regulation.⁵

Active and intelligent functions. When longer shelf life or quality monitoring would meaningfully cut food loss, active and intelligent functions earn their place. Active packaging that carries antimicrobial or antioxidant agents, or that manages gases and moisture, has been shown to extend

shelf life across many food types, while intelligent indicators and sensors, time–temperature indicators and freshness sensors among them, sharpen traceability and head off needless disposal.^{21,22} Newer work pairs these systems with data tools and artificial intelligence to help with material choice, shelf-life prediction, and quality control, and reports measurable cuts in food waste and greenhouse-gas emissions in prototypes, although getting the electronics back out at end-of-life is still a problem.^{10,23} Every such function has to be weighed against the impact it adds and any trouble it causes for recycling.

Circularity design. Last, designers fix the intended end-of-life route, whether reuse, mechanical or chemical recycling, or organic recovery, and then work backwards from it, making sure the package matches the infrastructure named in Layer 1. High rotation rates and established return logistics can dramatically reduce impacts through reuse, and studies comparing reusable transport crates with single-use boxes show steep reductions in carbon, water and waste in realistic pooling scenarios ²⁸. Reuse is not a universal winner, though. Its advantage hangs on trip counts, washing, and transport, which is one more reason every case has to be judged on its own terms.

4.5. Layer 4 Evaluation and trade-off analysis

The fourth layer judges the candidate concepts and brings their trade-offs to the surface. Four assessments work together. First, a screening pass throws out concepts that fail on safety or feasibility from the start, such as materials that cannot meet migration limits for the food they will touch or that have no workable supply.⁹ Next, LCA quantifies life-cycle impacts for each remaining concept against the functional unit set in Layer 1.^{8,27} Because protection is the whole point, that LCA has to be tied to food-waste outcomes: it should estimate the loss rate each concept implies and credit the avoided burden of the food that is not wasted, as Figure 3 illustrates.^{7,29} A cost and manufacturability check then covers the economic side, including any change in producer-responsibility fees.⁵

Life-cycle phases of the packaging-food system

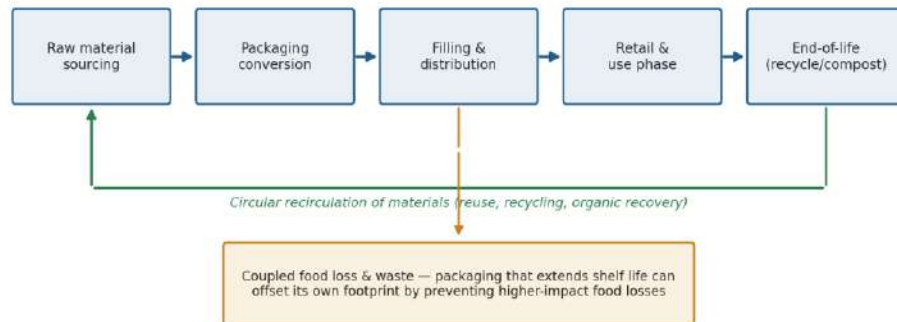


Figure 3. Life-cycle phases of the packaging–food system. Materials may recirculate through reuse, recycling, or organic recovery, and packaging performance is coupled to food loss and waste, which can dominate total system impact.

Since the four assessments report in different units and pull in different directions, the framework folds them together with multi-criteria decision analysis. MCDA puts the weighting of objectives, set back in Layer 2, out in the open, and returns a comparable score for each concept while keeping the underlying numbers visible, so a decision maker can see what is being given up for what. Pairing LCA with MCDA is well worn in sustainable-packaging and supply-chain research, and it suits this problem precisely because the task is to balance aims that cannot be reduced to one number rather than to maximise a single one.²⁵ A worked example follows in Section 5.

4.6 Layer 5 Decision and validation

The final layer makes a choice but treats it as provisional. The selected design goes through pilot testing, to confirm shelf life, barrier behaviour, and safety under realistic conditions, and then, once it is in use, through monitoring of real loss rates, recycling outcomes, and cost. Those results flow back to Layer 1, so the framework behaves like a learning loop instead of a one-off sum. That iterative habit matters because the inputs that drive the answer, recycling infrastructure and consumer behaviour among them, shift over time and differ from place to place.^{12,24}

4.7 How the layers interact

Although they are presented in sequence, the layers form a connected system, not a one-way pipe. The objectives established in Layer 2 limited the levers explored in Layer 3. The evaluation in Layer 4 will often show no candidate is good enough on the weighted objectives, and the team will

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have to go back to Layer 3 for new concepts or back to Layer 2 to rethink the weighting. Each subsequent layer passes through the available end-of-life routes particularly under the context drawn in Layer 1 as a fixed constraint. In Layer 5 the validation loop closes the loop in time, passing monitored results to the assumptions for the next time. And it's this wiring that enables the framework to consider the real messiness of packaging decisions without turning into a rigid checklist or a shapeless debate^{24,25}.

5. Operationalising the framework

5.1 Indicators and metrics

To make the framework usable, it needs a fixed set of indicators with units and data sources so that one evaluation can be compared with another and checked. Table 3 presents a reduced set for the three dimensions. It is intentionally brief. Experience with sustainability assessment shows that a short list of well understood indicators is more useful in practice than a long list for which reliable numbers cannot be provided by anybody. The transparency principle requires that each indicator be reported with its data quality and its main assumptions.

Table 3. *Proposed indicator panel for the FPSDF. FU = functional unit.*

Indicator	Unit	What it captures	Typical data source
Carbon footprint	kg CO ₂ -eq / FU	Climate impact across life cycle	LCA (e.g., Ecoinvent + primary data)
Cumulative energy / water	MJ; L / FU	Resource intensity	LCA inventories
Recycled content	% by mass	Use of secondary materials	Bill of materials / supplier data
Recyclability	% recyclable in market	End-of-life compatibility	Design-for-recycling protocols
Shelf-life	days	Protective performance	Storage trials
Food loss rate	% of product	Coupled food-waste effect	Trials / supply-chain data
Migration compliance	pass/fail vs. limit	Chemical safety	Migration testing
Total cost	currency / FU	Economic viability	Cost model incl. EPR fees

5.2 Regulatory anchoring

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Compliance is a precondition, not an objective to be traded away, so the framework treats the regulatory context as a constraint and applies it in Layers 1 and 4. Table 4 picks out selected requirements of the EU PPWR, which is a good marker of where regulation is heading: common rules on recyclability and minimisation, floors for recycled content, reuse duties in some sectors, limits on substances of concern, and producer responsibility with fees tuned to environmental performance.⁵ A designer working across several markets has to map the relevant duties early, because they can rule out an otherwise appealing concept and can tilt the economics through fee modulation.

Table 4. *Selected requirements of the EU Packaging and Packaging Waste Regulation (Regulation (EU) 2025/40) and their design implications.*

PPWR area	Direction	Design implication
Recyclability (by 2030)	All packaging recyclable at scale	Favour mono-materials; design for recycling
Recycled content	Minimum % in plastic packaging	Specify and verify secondary feedstock
Packaging minimisation	Reduce to functional minimum	Eliminate void space and superfluous layers
Reuse / refill	Targets in selected sectors	Assess reusable systems where logistics allow
Substances of concern	Restrictions (e.g., PFAS limits)	Screen additives and coatings for compliance
Producer responsibility	Eco-modulated EPR fees	Lower fees reward recyclable design

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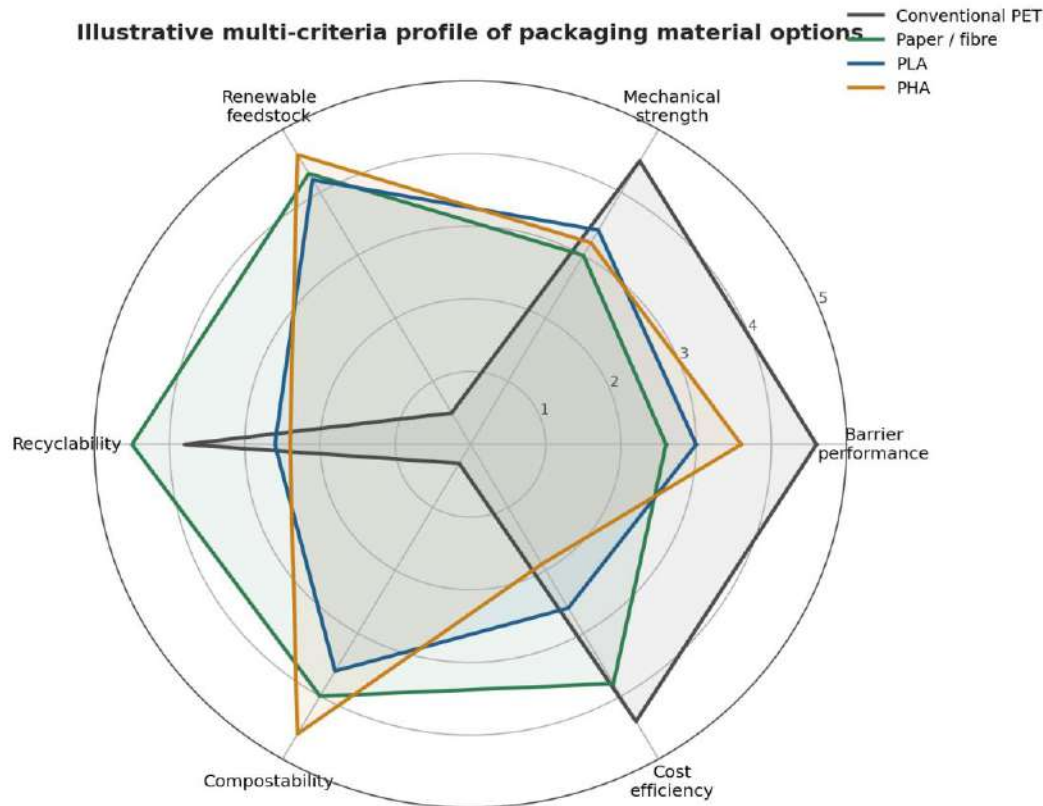


Figure 4. Illustrative multi-criteria profiles of four packaging material options. Scores (1–5) are indicative and for demonstration only; no option dominates across all criteria, motivating structured trade-off analysis.

5.3 Worked example: a chilled meat tray

To illustrate how the framework differentiates between options, consider the design of a tray for a chilled red-meat product sold within a single country where mechanical recycling of rigid plastic is well established but industrial composting is not widely available. The functional unit is the delivery of 1 retail portion to the consumer with minimal loss at a target 12-day shelf life. Layer 3 generates three candidates: (A) a conventional multi-material plastic tray with high barrier and long shelf life; (B) a recyclable single-material plastic tray with recycled content and active oxygen scavenging function to hold shelf life; and (C) a fibre tray with a compostable bio-based film lining. Layer 4 screening removes migration limits for all three. But Concept C has an immediate problem. Its compostable liner has no local composting route and will be landfilled or burned. The end-of-life benefit it was chosen for never happens. Fibre-and-liner combinations can muddle fibre recycling, so its recyclability suffers too. Concept found for coupled LCA with food loss counted Strong on shelf life, but weak on recyclability and recycled content. Concept C lower in fossil

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feedstock, but missing infrastructure and a slightly higher modelled loss rate short of the impact cut it promised. Concept B well balanced, holding shelf life through its active function, while remaining recyclable and carrying recycled content. Table 5 provides an example of MCDA for this perishable, recycling-oriented setting, where objectives are weighted, with the greatest weight on shelf life and recyclability.

Table 5. *Illustrative weighted MCDA for the chilled meat tray example. Scores (1–5) and weights are for demonstration only; concept B achieves the highest weighted total in this context.*

Criterion (weight)	Weight	A: multi-material	B: mono-material + active	C: fibre + liner
Carbon (incl. food loss)	0.20	3.5	4.0	3.0
Recyclability	0.25	1.5	4.5	2.5
Recycled content	0.10	1.0	4.0	2.0
Shelf-life / loss	0.25	4.5	4.5	3.5
Cost	0.10	4.0	3.5	3.0
Information / clarity	0.10	3.0	3.5	4.0
Weighted total	1.00	3.03	4.23	2.98

Judged on a single issue, concept C might win for looking “greenest” by feedstock, and concept A might be kept for its long shelf life. The framework instead points to concept B as the best-balanced choice here, because it holds the protective performance that keeps food from being wasted while meeting the recyclability and recycled-content aims that fit the local infrastructure. The result is tied to its context. Make industrial composting widely available and the product less perishable, and concept C could come out ahead. The framework's worth is not in handing down a universal ranking. It is in making the reasons for a decision explicit, checkable, and open to revision. Figure 5 summarises the sequence.

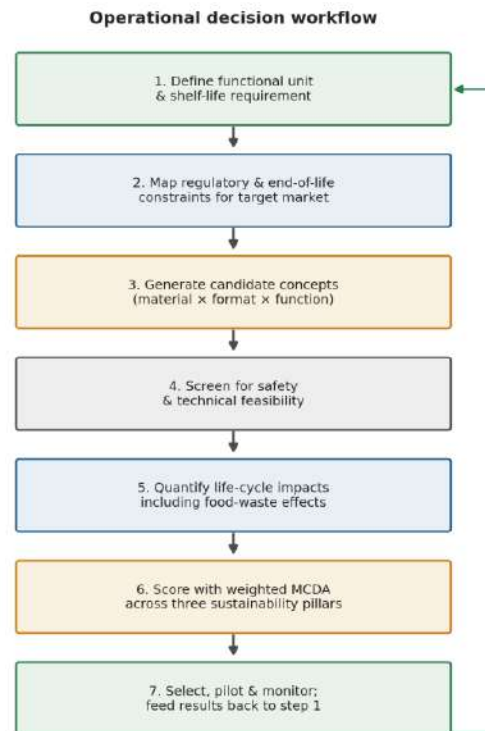


Figure 5. Operational decision workflow for applying the FPSDF, from defining the functional unit to selection, piloting, and feedback.

5.4 Generality across product archetypes

The worked example is based on one product, but the framework is meant to travel. The flexibility is in Layer 2, where the weighting of objectives is adjusted to the product and market, instead of being set once and for all. Table 6 shows how the leading objectives move across common food-packaging archetypes. For shelf-stable dry goods, where spoilage is unlikely, using less material and being recyclable tend to lead. For highly perishable chilled and fresh products, extending shelf life to avert loss takes over, since the food's footprint towers over the packaging's.⁷ For beverages, reuse and refill systems and recycled content often decide matters, shaped by both regulation and infrastructure.^{5,28} The same five layers and the same indicator panel apply throughout; only the weights and the set of feasible levers change. Keeping a stable process apart from a context-specific weighting is what gives the framework both consistency and reach.

Table 6. Illustrative shift in dominant objectives across food-packaging archetypes; the same framework process applies, with context-specific weighting.

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Product archetype	Typically dominant objectives	Levers most often decisive
Shelf-stable dry goods	Material minimisation; recyclability	Mono-material formats; mass reduction
Chilled perishables	Shelf-life extension; loss avoidance	Barrier and active functions; format
Fresh produce	Loss avoidance vs. minimal packaging	Right-sized protective design; fibre formats
Beverages	Reuse/recycled content; recyclability	Refill systems; recycled-content specification
Frozen foods	Barrier and integrity; recyclability	Recyclable barrier structures; design-for-recycling

6 Discussion

6.1 Contributions

The framework's main contribution is that it joins things up. It does not lengthen the catalogue of materials or methods. It wires them into one coherent decision process that holds the three sustainability dimensions in view at once and states their trade-offs out loud. Three features mark it off from material-substitution thinking. It anchors evaluation in a functional unit defined by the food delivered rather than by the package, which heads off the familiar mistake of comparing packages while forgetting what they are for.⁷ It ties packaging performance to food-waste outcomes, on the recognition that for many products avoiding food loss is the strongest lever there is.^{7,29} And it treats compliance and end-of-life infrastructure as hard limits, so the answers it gives can actually be realised in the intended market and not only in principle.^{5,15}

6.2 Barriers and enablers

Several things stand in the way of using the framework in earnest. Data is most important. Credible LCA and food-loss coupling require inventory and trial data that smaller producers may not have and any uncertainty in those inputs carries straight through into the MCDA. Shortcomings of bio-based materials, limiting where they can supplant conventional plastics, include barrier performance, heat resistance and cost.^{19,31} With it, the “right” answer shifts, complicating product decisions sold internationally, because infrastructure varies from market to market and changes over time. And the distance between what appears sustainable and what actually is creates a genuine risk: designs built for real impact may be penalized by consumers, while designs that merely appear green may be rewarded. Meanwhile the enablers are getting stronger^{11,12}.

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The shift from directives to harmonised regulation will reduce fragmentation and reward design for recycling via performance-based fees, aligning commercial and environmental incentives^{4,5}. The progress in active and intelligent packaging and its connection with data tools widens the possibilities of extending shelf life and monitoring quality, which directly feeds the food protection dimension^{10,21,23}. Maturing reuse schemes and steadier recycling and bio-based supply chains add to the circularity options open at Layer 3.^{18,28} The framework is built to take these in: new levers and new indicators can be slotted in without disturbing its structure.

6.3 Relationship to existing frameworks and standards

The FPSDF doesn't replace existing methods, it does them. In Layer 4, LCA remains the driver of environmental measurement and the screening rules are given by the recognized design-for-recycling protocols and migration-testing standards.^{8,9} The three-dimension structure used here builds on the earlier conceptual work naming the dimensions of sustainable food packaging. The circularity levers and the handling of reuse are informed by circular-economy and supply-chain studies.^{3,24,25} What the framework adds is the binding step, tying these pieces into one repeatable decision sequence anchored on a food-defined functional unit and explicit weighting of objectives. That makes it a complement to regulatory instruments such as the PPWR, which set the limits and incentives but do not, on their own, tell a designer how to balance competing aims for one product.⁵ Seen this way, it sits beside the existing tools rather than against them.¹⁰

6.4 Limitations and future work

The framework is conceptual, and it has been demonstrated rather than tested in the field. The worked example uses indicative scores to show the logic, not measured data, and the MCDA weights are unavoidably matters of judgement, so any real application should run a sensitivity analysis on both weights and scores. Useful next steps include case studies across contrasting food categories and markets; agreed, lightweight default datasets that lower the barrier to coupled LCA; ways of carrying uncertainty through the MCDA; and better social indicators, which lag behind the environmental and economic ones. Validation done together with industry and waste-management operators, in keeping with the co-design principle, would show whether the framework improves real decisions and whether the people who have to act on its outputs accept them.

7 Conclusions

Sustainability in food packaging cannot be settled by picking the right material. It is a design problem with several dimensions, environmental conservation, food protection and safety, and social and economic value, which have to be reconciled, often while pulling against one another, and always for a particular product in a particular market. This paper has designed a Food Packaging Sustainability Design Framework to meet that problem head-on. By splitting the decision into five connected layers, context, objectives, levers, evaluation, and decision, and running four principles through all of them, life-cycle thinking, do-no-significant-harm, transparency, and co-design, the framework carries a practitioner from a sustainability ambition to a choice that can be defended. It is distinguished from narrow substitution by being anchored on a food-defined functional unit, coupling packaging to food-loss outcomes, and treating compliance and infrastructure as limits, thus avoiding shifting burdens from one place to another. The worked example demonstrates that it can yield balanced solutions that would be missed by a single-issue view, while keeping the basis of the decision open and revisable. Materials, technologies and rules will keep evolving. Rather than a static checklist, an adaptable scaffold of this type provides a durable foundation for designing food packaging that is demonstrably more sustainable.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No new primary data were generated; all sources are cited in the reference list.

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