Attainable Sustainable: Using Electron Beam Technology in Compostable Flexible Packaging

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Abstract

Sustainable practices, including material reduction and the use of bio-based, recyclable, or compostable materials, are forefront in the minds of both consumers and the packaging industry. This is especially true for flexible packaging, which has traditionally consisted of multi-layer, non-recyclable structures. In this study, the use of ebeam technology in the life cycle of a compostable, flexible package was investigated.

Introduction

In recent years, the packaging industry has experienced a consumer backlash regarding its use of plastics.[1-3] In response, companies have made sustainability pledges that include goals such as reducing their plastic consumption, reducing production waste, and increasing the amount of recycled plastic in products.[4-6] These strides toward a more environment-friendly future are commendable but are not always easily achieved. While consumers call for less single-use packaging waste, their expectations of how packaging performs – that food remains fresh, products remain undamaged, and marketing remains eye-catching – have not waivered.

Electron beam (ebeam) technology is a multi-faceted tool that is well-suited for aiding the achievement of sustainability goals.[7-12] For instance, ebeam crosslinking can improve mechanical properties, allowing for reduced plastic consumption by down-gauging film. It can also be used to increase compatibility between different polymers as well as virgin and recycled polymer blends. Ebeam-induced chain scission can be used to recycle materials through degradation. Scrap polytetrafluroethylene (PTFE), for example, is irradiated to create micropowders that become ingredients in lubricants, inks, and coatings.

In flexible packaging production, ebeam is a useful tool in accomplishing one of the industry's more recent trends – mono-layer and/or mono-material packaging. Traditionally, flexible packaging has relied on multi-layer, non-recyclable structures to achieve the wide array of demands placed on a single pouch, from moisture and oxygen barriers to tear strength and sealability.[13,14] Mono-material structures are expected to meet these demands with a single type of plastic so that they can be more easily recycled or composted, but it is an ambitious challenge. One way ebeam can help meet this challenge is by altering a polymer without any added chemistry. Ebeam crosslinking and chain scission provide property tuning that can be controlled through a selected substrate depth; a common example of this application is crosslinking an outer layer of polyethylene (PE) to increase heat resistance without affecting the sealing temperature of the inner PE layer. Additionally, ebeam can be used to polymerize inks and overprint varnishes (OPVs) without the need for initiators or solvents and with comparatively little energy.[15-18] OPVs are a sustainable alternative to lamination. Because inks and OPVs make up such a small fraction of the overall package, they've been shown to not hinder recyclability.[19,20]

Accompanying the mono-material trend to make flexible packaging recyclable is a movement for compostable flexible packaging. Instead of relying on the ability to effectively repurpose packaging plastics, compostable packaging seeks to optimize the disposal of packaging waste by using biodegradable polymers. Ebeam is less tested as a production solution in compostable packaging; however, there are several ways this technology may benefit the industry. Similar to recyclable packaging, it is expected that ebeam-cured inks and OPVs can be utilized without impacting the biodegradability of compostable packaging. Furthermore, ebeam could possibly result in accelerated disintegration if the packaging is exposed to high doses after consumer use.

Molecular weight reduction by chain scission is a known effect of ebeam irradiation on cellulose, a common compostable material.[21] It is hypothesized that this degradation could be leveraged to decrease composting time. As compostable plastic packaging gains popularity, a reduction in the multi-week disintegration process may be imperative for the current infrastructure to keep up with the increasing supply. According to a survey conducted by BioCycle in 2018, of the 185 identified food waste compost centers in the U.S., only 53 reported being able to accept compostable plastics.[22] In addition, accelerating plastic disintegration should make it a more profitable enterprise; high volume turnover will help offset costs, such as sorting non-compostable plastics out of the feedstock.

In this study, the application of ebeam in the production and destruction of a mono-material, compostable flexible food packaging structure was investigated. Low doses of ebeam were used to cure matte and gloss OPVs on the compostable film, which was then tested to determine if the OPV inhibited or impeded compostability. Moreover, high doses of ebeam were used to induce chain scissioning in the packaging structure (film/ink/ebeam-cured OPV) to ascertain whether such degradation at the end-of-life could efficiently reduce compost times. Puncture strength was measured as a means of analyzing the ebeam degradation.

Experimental

Materials

The substrate material used in this study was NatureFlex™ NK 120 gauge (NK120, Futamura).[23] NK120 is a transparent cellulose film coated with PVdC for moisture and gas barrier properties. It was selected because it is suitable both as a laminate and for mono-layer flexible packaging applications. NK120 is certified as industrial and home compostable. The primer used was DigiPrime® 050 (Michaelman).

The ink used was the CMYK Indigo ElectroInk digital ink set (Hewlett-Packard).[20] These digital inks are in-direct food safe and certified as industrial and home compostable.[24,25] In addition, the digital printing process has some environmental advantages over analog methods, including less material waste, low energy consumption, and no printing plates or cylinders.

The overprint varnishes (OPVs) used in this study were EHG-2601 (EG, DBT Coatings) and EMQ-3710 (EM, DBT Coatings) with high gloss and matte finishes, respectively.[26,27] These ebeam-curable OPVs were chosen because they are used in the flexible food packaging industry and are formulated to protect and highlight the digital inks. Both OPVs meet ultra-low migration standards, are indirect-food-contact safe, and are free of initiators and solvents.

Methods

Sample Preparation

NK120 film was coated with primer and printed using a HP Indigo 20000 digital press. Unprinted NK120 film was also used for some samples. Both the printed and unprinted film were then corona treated at 13.8 W/in, OPV was applied with an indirect gravure coater, and lastly the OPV was cured at 30 kGy and 115 kV using a Broadbeam EP electron beam pilot line (PCT Ebeam and Integration). Oxygen levels were kept to < 200 ppm using a flow of 99.999% pure N_2 in the beam. The EM OPV was applied using a 5 BCM, 400 line ceramic anilox with a resulting coat weight of approximately 2.0 g/m^2. The EG OPV was applied using a 10 BCM, 200 line steel anilox with a resulting coat weight of approximately 3.5 g/m^2.

Additionally, some samples were exposed to ebeam for a second time for a post-treatment, which was intended to reduce composting time through degradation of the cellulose film. The post-treatment was done in air, at 200 kV, 50 ft/min, and at doses ranging from 50 to 400 kGy. 200 kV was chosen as an accelerating voltage to ensure an equal dose distribution through the complete thickness of the film.

Compostability Testing

To determine the influence of the samples on the composting process, samples were composted by Organic Waste Systems (OWS) following the test method detailed in ISO 16929:2013.[28] The pilot-scale aerobic composting test consisted of organic biowaste (a mixture of vegetable, garden, and fruit waste) in a 200-L composting bin monitored through temperature and exhaust gas composition for 12 weeks. The mixture was turned by hand every 1 to 2 weeks. In order for the test to be deemed valid, the temperature must remain between 60-75°C during the first week and below 65°C thereafter, with the minimum temperature remaining above 40°C for at least 4 consecutive weeks. Photographs were taken on a weekly basis to visually evaluate the percentage of disintegration the sample material had undergone. Because of this qualitative evaluation metric, the results of this compostability testing serve only as an indicator of whether the sample will pass a quantitative (mass balance) test. The unprinted samples tested for compostability are listed in Table 1 and the printed and post-treated samples are listed in Table 2.

Table 1. Unprinted samples tested for compostability.

Sample	Film	OPV	Ebeam Settings
A	NK120	–	–
B	NK120	–	30 kGy / 115 kV
C	NK120	EG	30 kGy / 115 kV
D	NK120	EM	30 kGy / 115 kV

Table 2. Printed and post-treated samples tested for compostability.

Sample	Film	OPV	Ebeam Settings	Post-treatment Ebeam Settings
A	NK120	EG	30 kGy / 115 kV	–
B	NK120	EG	30 kGy / 115 kV	150 kGy / 200 kV
C	NK120	EG	30 kGy / 115 kV	300 kGy / 200 kV

Puncture Testing

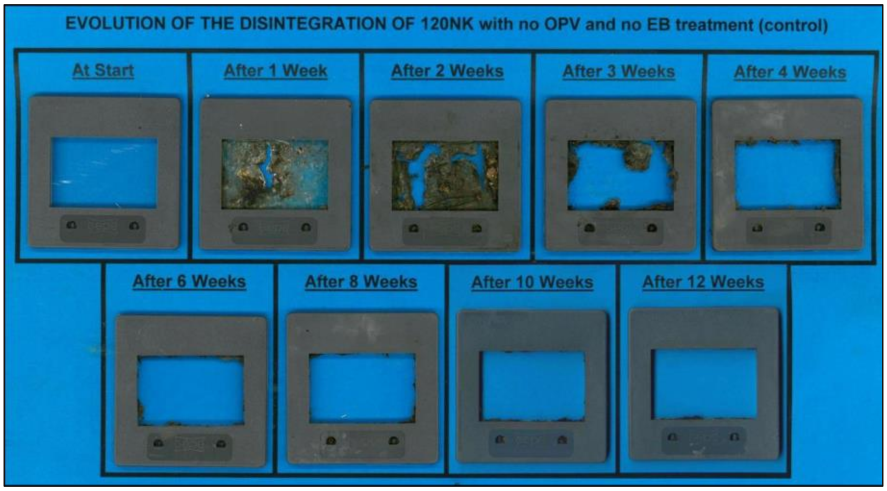
Puncture resistance was used as a measure of film strength after ebeam exposure. 6.5-inch squares of sample material were held taught in a fiberglass board frame (Micarta) using a rubber O-ring with a 5-inch outer diameter and 0.210-inch width. The frame had a 4-inch diameter circular window exposing the sample. A compressive load was applied to the center of the exposed sample at a rate of approximately 3 to 4 lb/s using a rounded probe with an arc 1.094 inches wide and 0.270 inches high. A broad probe was chosen to gain better resolution of the film strength lost at varying ebeam doses. The applied load was measured using an Uline platform dial scale (model no. H-176). The recorded value was taken as the maximum load applied before the sample ruptured, and the probe was able to push through the sample. For each sample condition, 5 repetitions were completed, and the values reported are an average of those repetitions. The error reported is the standard deviation of the 5 repetitions.

Results and Discussion

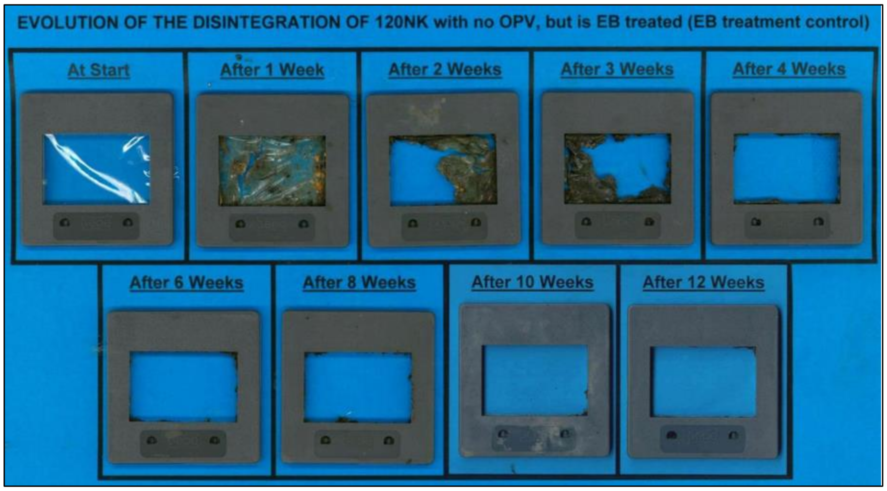
The purpose of this study is to establish ebeam-curable OPVs can be used in the production of compostable flexible food packaging without significantly impeding the compostability of the packaging. Furthermore, ebeam exposure was investigated as a means of accelerating the disintegration during composting. High doses were used to weaken the compostable film through chain scission.

Packaging Compostability

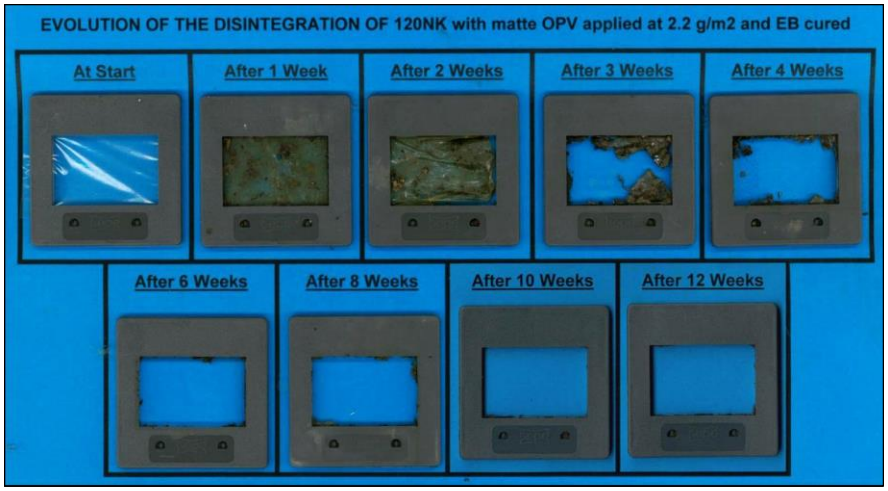
An integral aspect of using ebeam-cured OPVs in compostable flexible packaging is demonstrating that the OPVs do not inhibit or significantly impede the disintegration of the compostable film. In addition, because ebeam is well known to interact with cellulose, it is also important to establish what effect an ebeam curing dose (30 kGy) has on the compostability of the film.[21, 29] To this end, select samples (Table 1) were composted, and their disintegration progress visually documented (Figure 1).


EVOLUTION OF THE DISINTEGRATION OF 120NK with no OPV and no EB treatment (control)
At Start
After 1 Week
After 2 Weeks
After 3 Weeks
After 4 Weeks
After 6 Weeks
After 8 Weeks
After 10 Weeks
After 12 Weeks

(A)


EVOLUTION OF THE DISINTEGRATION OF 120NK with no OPV, but is EB treated (EB treatment control)
At Start
After 1 Week
After 2 Weeks
After 3 Weeks
After 4 Weeks
After 6 Weeks
After 8 Weeks
After 10 Weeks
After 12 Weeks

(B)


EVOLUTION OF THE DISINTEGRATION OF 120NK with matte OPV applied at 2.2 g/m2 and EB cured
At Start
After 1 Week
After 2 Weeks
After 3 Weeks
After 4 Weeks
After 6 Weeks
After 8 Weeks
After 10 Weeks
After 12 Weeks

(C)

(D)

Figure 1. Results of the compostability testing for unprinted samples. After 6 weeks, the OPV-coated samples (C and D) have the same amount of uncomposted material left in the frame as the plain film (A). Sample conditions are listed in Table 1.

Comparing the control film (Figure 1, A) to a film that's received a curing level dose (B), the ebeam dose does not appear to have a significant effect. After 2 weeks composting, the ebeam sample (B) appears to have slightly more disintegration than the control (A), but those impressions flip after 3 weeks. After 4 weeks, both samples are almost completely disintegrated, with only a few small pieces of film still left at the edges of the test frame.

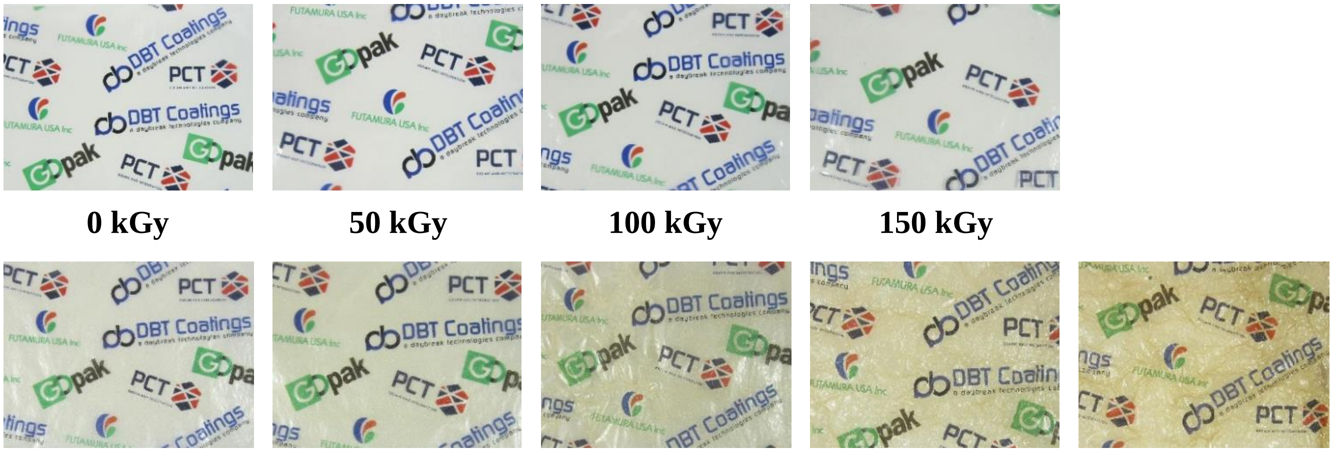
The addition of an ebeam-cured OPV also does not appear to significantly impact the disintegration time of the film. The majority of both the EM-coated (Figure 1, C) and EG-coated (D) samples was disintegrated after 4 weeks. Both samples retained slightly more film at the edges of the test frame after 4 weeks than the control (A); however, by the end of 6 weeks (a 5-week photo not being included in the test results), the disintegration levels of the OPV-coated samples and the control are visually the same.

Post-treatment of Packaging

With the compostability testing providing positive qualitative results and demonstrating that ebeam-cured OPVs can be effectively used in the production of compostable flexible food packaging, the potential of ebeam to affect a package after consumer use was considered. Composting, even on an industrial scale with controlled conditions, is a time-intensive, multi-week process. Accelerating the disintegration of material could allow compost facilities to efficiently convert a higher volume of packaging with little to no changes in infrastructure.

Visual Effects

The degradation of the compostable packaging structure (film/print/OPV), caused by ebeam irradiation, was first evaluated visually (Figure 2). Samples exposed to an ebeam post-treatment dose of 50 to 400 kGy were compared to a control (Figure 2, 0 kGy).



0 kGy **50 kGy** **100 kGy** **150 kGy**

200 kGy **250 kGy** **300 kGy** **350 kGy** **400 kGy**

Figure 2. Visual effects of ebeam post-treatment. Samples are coated with ebeam-cured EG OPV (Table 2).

Remarkably, there are no discernible effects of the ebeam post-treatment until 150 kGy. At 150 kGy, there is some slight discoloration of the film and noticeable cracking of the OPV. As higher post-treatment doses are applied, the yellowing of the film intensifies and the film shrinks and wrinkles.

Puncture Strength Reduction

Puncture strength was used as quantitative measure of the scissioning effect caused by high doses of ebeam. As chain scission increases, the strength of the film is expected to decrease. Figure 3 shows a clear correlation between the puncture resistance of the compostable film and the dose level of the ebeam post-treatment. Comparing the plain NK120 film to the plain film after receiving a curing-level dose (Figure 3, grey square and triangle, respectively), there is an approximately 5 lb decrease in puncture resistance. Note, there is some overlap of the error in these measures. No significant difference is seen when print and EG OPV is added to the construction (black circle, 0 kGy). As the ebeam post-treatment dose is increased, the puncture force decreases. The relationship of these two variables follows the trend line of a second order polynomial with an R^2 value of 0.9869.

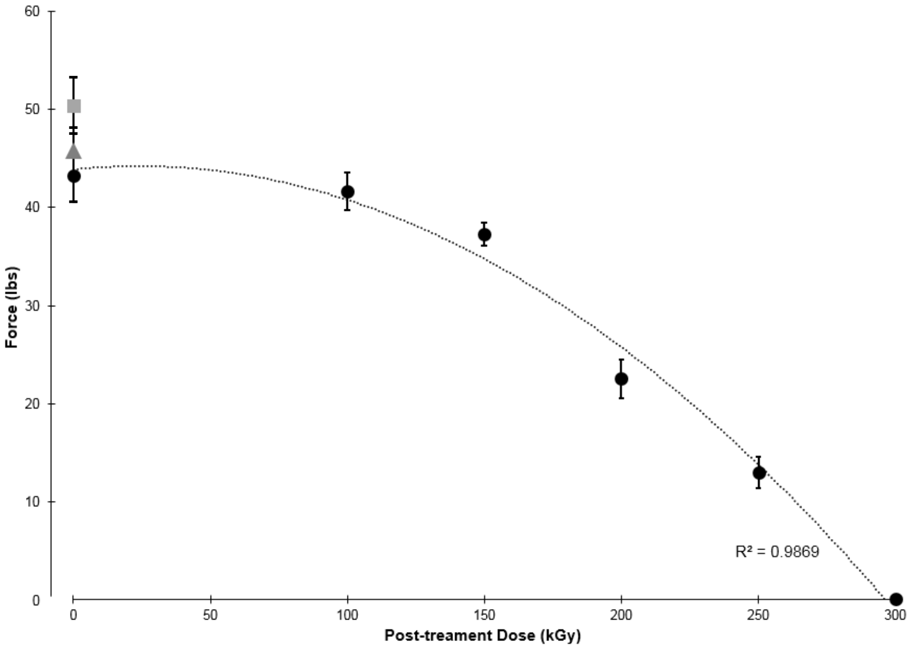


Figure 3. Puncture resistance of the compostable packaging film decreases as the ebeam post-treatment dose is increased. The grey square (■) and triangle (▲) are samples A and B of Table 1, respectively. The black circles (●) represent samples of the construction listed in Table 2.

Interestingly, there is almost no loss of puncture resistance between the 0 kGy and 100 kGy post-treatment dose. While ebeam dose levels are generally kept quite low for curing (~30 kGy), this result, along with the visual results, demonstrates that there is potentially a much larger ebeam operating window than previously thought. The effect of ebeam on other mechanical properties would need to be investigated to confirm. However, a larger operating window could be a beneficial option for improving ink and coating performance through enhanced crosslinking.

Compost Results

Based on the results of the puncture strength testing, three samples were chosen to test the effect of ebeam post-treatment on the compost rate of the packaging structure, a control and two different post-treatment doses (Table 2). Currently, the test is ongoing; however, after only 1 week, significant differences can be observed (Figure 4).

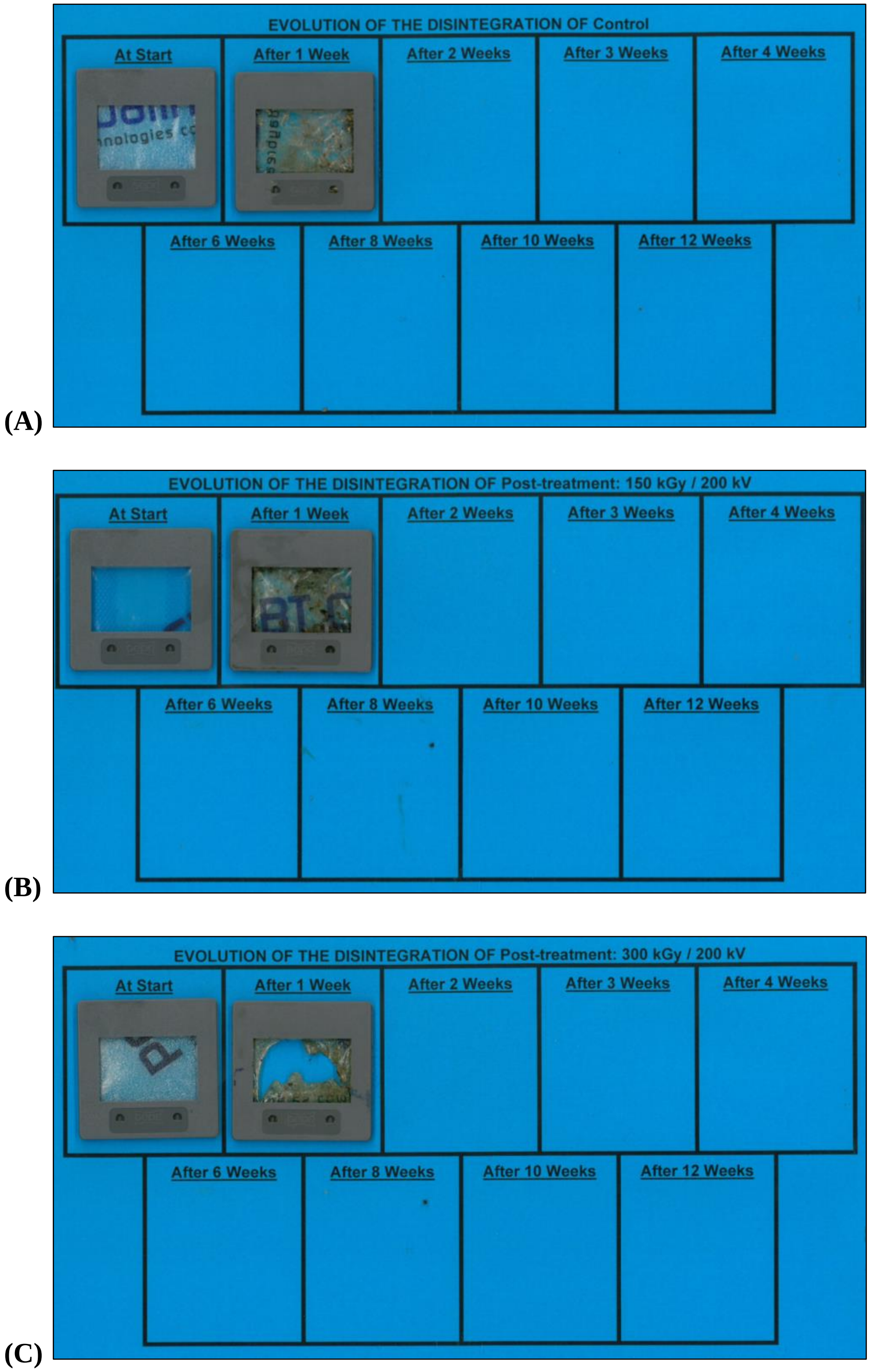


Figure 4. Results of the compostability testing for printed samples with ebeam post-treatment. After 1 week, the 300 kGy post-treatment sample (C) shows significant disintegration, while the control (A) and 150 kGy post-treatment samples (B) are completely intact. This test has 11 weeks remaining. Sample conditions are listed in Table 2.

While the control and 150 kGy post-treatment samples have turned brown, no disintegration has yet occurred. Contrastingly, the 300 kGy post-treatment sample has already experienced a significant amount of disintegration. The compostability test has 11 weeks remaining, but thus far using a high dose ebeam post-treatment to increase the rate of disintegration of compostable material looks promising.

Conclusions

In conclusion, a qualitative compostability test was conducted and showed that ebeam-cured OPV did not make a significant impact on the compost rate of a cellulose film. These results indicate that the reviewed structures would likely pass a quantitative, mass balance test.

Furthermore, a post-treatment ebeam dose was evaluated as a potential means of increasing the composting rate of the flexible packaging structure. The degradation of the film was confirmed visually as well as by demonstrating that puncture strength decreased as the post-treatment dose was increased. The qualitative compostability testing of these post-treated structures is ongoing; however, after only one week of testing, high-dose ebeam post-treatment was shown to positively impact the composting rate.

In addition to quantitative compostability testing, future work in this arena includes broadening the scope of OPVs, inks, and compostable substrates investigated. The optimal ebeam dose necessary to degrade a compostable structure is expected to be dependent on the chemistry of the film and should also be evaluated for a wide variety of compostable material.

The broad applicability of ebeam was demonstrated by establishing the technology as a tool for both the production of compostable packaging as well as the degradation of it after use. As the packaging industry endeavors toward a more sustainable future, versatile technologies, such as ebeam, provide companies flexibility in developing new avenues to achieve their recycling and composting targets.

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