NIFA USDA SBIR phase 1

Excerpts from the Final Technical Report

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Executive summary

Radical Plastics has made significant progress towards the development of soil biodegradable mulch films. We met the SBIR phase 1 set goals: 1) Developed a mulch film with the required balance of physical and optical properties and targeted biodegradation to support the 4-6 mo growth cycle; 2) Ran field studies with the best film candidates to demonstrate easy application and positive effect on plant growth; 3) Demonstrated no film adhesion related problems on harvested fruits and vegetables; 4) Developed accelerated testing to correlate with natural exposure and 5) Initiated testing per EN17033 standard for mulch films.

Despite a very difficult year, no major delays with the project were encountered. We had to replace some field testing contractors and testing labs due to the COVID restrictions, i.e. Cornell College of Agriculture was replaced with the University of Florida in Live Oak (Robert Hochmuth's team has grown over 2000 watermelons with Radical Plastics mulch films). The soil respirometry tests ended up being run by the Impact Solutions in Scotland, UK and by LMPE lab in Pisa, Italy, one of the most experienced labs specializing in the soil biodegradability and ecotoxicity testing. Lab scale film manufacturing was also conducted by a contractor in Birmingham UK, when the University of Massachusetts Lowell was closed.

Radical Plastics has produced over 25 rolls of 1 mil thick films (21" x 600 feet or 24" x1000 feet), which were tested in multiple locations through out the US from upstate NY

(Wegmans and Harris seeds) to Maine (Johnny's Selected Seeds) to Massachusetts (local farmers) to Northern Florida (university) to California (farmers). The grown vegetables and fruits included tomatoes, onion, garlic, squash, eggplants, watermelons and peppers. Very positive feedback was received from all testing partners. The film handled much better versus competitive starch films. A number of farmers came back asking for more film – a proof point for potentially recurring "sales".

Radical Plastics continues working on providing the data on soil and plant eco-toxicity and on the confirmation of biodegradation by respirometry. We have initiated business development work with LARTA, in parallel with working with the team of graduate students from UC Berkley, Haas School of Business – an opportunity won through the Cleantech to Market (C2M) competition. We completed the market analysis and techno-economic modeling, developed initial business strategy and initial commercialization plan.

The Radical Plastics founders (Yelena Kann and Kristin Taylor) have been selected as Activate Fellows. The Activate Fellowship is a 2 year program run by the Lawrence Berkley National Lab and MIT Lincoln Labs to support the most promising high impact technologies in the areas of energy and materials. Radical Plastics has hired one full time Materials Engineer and one coop student, along with a few part time specialists: analytical chemist, CFO, digital marketing and operations.

Progress Toward Original Work Plan

The overall progress can be seen in Table 1 below. The actions "completed as planned" are highlighted in green, "in progress" activities are highlighted in tan. In blue are updates since the interim report. Abbreviations: "UML" stands for UMass Lowell, "UConn" for University of Connecticut, LMPE is the environmental testing lab in Pisa, Italy. Impact Solution is the environmental testing lab in Scotland, UK.

As can be seen from the Table 1, the project was managed close to the planned timeline. Changes of contractors were due to the closings and COVID-affected facilities. The soil and plant toxicity data is expected by the end of February, 2021. Accelerated heat and UV tests as well as soil degradation in field are on-going as we are monitoring complete biodegradation of mulch films, which according to ISO 17033 should be done within 2 years and demonstrate no residual microplastics.

Table 1. Project timeline

			Q3'20			Q4'20			Q1'21		
Activity	**Where**	**Goal**	**Jul-20**	**Aug-20**	**Sep-20**	**Oct-20**	**Nov-20**	**Dec-20**	**Jan-21**	**Feb-21**	**Mar-21**
Phase 1 Formulation development		Demonstrate ability of programmed performance									
Small Compounding run	~~Uconn, UML Mexichem,~~ Radical Plastics	Match required biodegradation profile									
Small scalte Film extrusion	Aquapak, CharterNex	Produce 1mil film									
Film properties testing	~~UML~~ Aquapak, Endicott College	Tear, strength, elongation confirmation									
Accelerated heat testing	Radical Plastics	Shelflife modeling									
Accelerated testing, UV	Applied Optix, OH	build correlations with natural aging									
Accelerated testing, UV	Radical Plastics	Accelerated testing									
Biodegradation in soil, field	~~Cornell, Ithaca, NY~~ Univ. of Florida	meet ISO 17556									
Chemical transformation, IR, Luminescence	Radical Plastics	Confirm efficiency of abiotic stage									
Respirometry, metals and C/N	~~Cornell, Ithaca, NY~~ Impact Solutions, LMPE	soil biodegradability ASTM 5988-18									
Testing for heavy metals, mineral composition	~~Cornell, Ithaca, NY,~~ UML	compilance with EPA and EN regulations									
Soil microbial and eathworm toxicity	~~Cornell, Ithaca, NY~~ Impact Solutions, LMPE	meet ASTM E1676									
Plant toxicity	~~Cornell, Ithaca, NY~~ Impact Solutions, LMPE	Barley, cress tests									
Phase 1 review and report to USDA/NIFA											
Phase 2 Scale up, customer validation											

During the course of the project we have made and analyzed the performance of two pilot runs of mulch films. The first pilot run produced films designated as CN20, CN21 and CN22. These films were tested from April 24 until the end of July in Northern Florida, and from April 19th through the end of July in Northern California. The second pilot run produced a film designated as CN24, which was tested in four locations thought the US: CA, Maine, upstate NY, MA. The testing partners, locations, crops, competitive films and film laying equipment are shown in Table 2. Based on the farmers feedback, the Radical Plastics films were more durable than the starch based alternatives, Bio360 and Organix, was easy to lay with regular equipment, provided good weed protection, moisture barrier, and started breaking down after the harvesting just as expected. No adhesion to the fruits and vegetables was observed (in contrast to Bio360 and Organix films).

Table 2 Radical Plastics mulch films field testing. Film applied from May through October 2020

Testing Partner	Geography	Crop(s)	Competitive Films	Film laying Equipment
Wegmans Test Farms	Canandaigua,NY	Tetra Squash	Bio360, PE	Tractor
Harris Seeds	Rocherster, NY	Multiple	PE	Tractor and by hand
Marini Farms	Ispwich, MA	Garlic, tomatoes	PE	Tractor
Living Acres Farm	Alfred Station, NY	Onions, Tomatoes	Bio360, PE	By hand
University of Florida	Live Oak, FL	Watermelons	PE	Tractor and by hand
Johnny's Selected Seeds	Winslow, ME	Onions, Bell peppers, Eggplant, Sw. Potatoes	Bio360, Organix, PE	Tractor
Kickback Farm	Rio Linda, CA	Onions, Tomatoes	PE	By hand

Problems Encountered

The respirometry, soil microbial and plant toxicity testing were all delayed by 2 months due to the problems with COVID-related closings and difficulty scheduling third party testing labs.

To be able to continue working on the project without interruption during COVID, Radical Plastics moved to a separate laboratory, purchased additional equipment and controlled the attendance of the team members. Several testing sites, labs, contractors were changed to enable expected progress.

The problems encountered for generation 1 films were lower tensile strength, elongation (CN20 and CN21) and insufficient opacity of the 1 mil black film (CN21). These problems were addressed in the generation 2 film, CN24, except for the dart impact, which still needs to be improved in order to meet the EN17033 requirements. We have made adjustments to the formulation and expect to confirm the performance and soil biodegradability during the 2021 pilot testing (hopefully phase 2 of SBIR).

Successes To Date

Understanding of the mineral used for catalyzing of abiotic degradation

Radical Plastics formulates its soil biodegradable films by compounding a special mineral-based catalyst with “barefoot” PE resins (either bio-based or fossil based) and adding required inhibitors, stabilizers, pigments and additives. The minerals come from the mining waste streams and are the mixtures of specific types of layered clays and minerals. The average particle size of the fine mineral matter we use for the compounding is 2 microns as blown film as thin as 10 microns is required for some applications. The minerals contain no toxic metals or substances of concern and have the required ratio of metals to promote abiotic degradation. The composition of the minerals used to produce the films in this study is measured by ICP (inductively coupled plasma) and is presented in Table 3. The data is based on the analysis of the mineral only – in the film it is added at a concentration of less than 1%.

Table 3 Composition of the active minerals used in the films formulation

	EN17033 upper limit, ICP, ppm	EPA40 CRF Pasrt 503 in soil				UML, ICP-OES, strong digestion, ppm			
		bio-solids	sludge						
Metal		upper limit, ICP, ppm	mex content, ppm	annual loading rates, lb/A/year	cumulating loading rates, lb/A	**lot 320**	**lot 202**	**slurry**	**lot 6040**
catalyst metals									
Fe			5,500			33,740	37,478	20,686	26,182
Mn						325	411	176	143
Cu	<50	<1,500	4,300	67	1,340	73***	0	39	12
Co		<20				0	0	0	0
Zn	<150	<2,800	7,500	125	2,500	163***	176***	98	164***
co-catalyst metals									
Ca						12,033	23,519	17,392	1,636
Al						15,366	15,718	5,373	12,682
Ba						650	528	59	282
Mg						6,992	8,974	2,647	3,273
K						3,902	3,167	1,863	4,909
Na						6,260	5,572	4,667	409
other elements									
As	<20.5**	<41	<75	1.8	36.6	0	0	0	0
Cd	<0.5	<39	<85	1.7	34.8	0	0	0	0
Cr	<50	<1,200	3,000	134	2,679	28	14	36	37
Hg	<0.5	<17	840	13.4	268	0	0	0	0
Ni	<25	<420	75	0.8	16	0	0	0	0
Mo	<1*	<18	57	0.8	15	0	0	0	0
Pb	<50	<300	420	14	375	0	0	0	0
P						203	NA	NA	139

*EN 13432 (2000)
**ASTM D6868-11
*** mineral is added at <1% in the plastic formulaiton

With more research on the topsoil regeneration and the soil fertility changes resulting from the intensive farming and the use of fertilizers, it becomes clear that to promote sustainable agriculture, less energy and chemical-intensive practices are need. Mixed-layer minerals are essential for maintaining the long-term soil fertility due to their unique cation exchanging capabilities and ability to retain fertilizers in soil.

In addition to the soil regeneration and fertility benefits, Radical Plastics has discovered that specific mixed minerals within the clay/layered minerals families, have abilities to catalyze the abiotic degradation of plastics used in agriculture. Once biodegraded, about 10% of the carbon in the plastic is converted to biomass and left in the soil. This, in combination with the minerals, is very beneficial to the health of the soil. Other 90% of the plastic's carbon is expected to convert into carbon dioxide and water, leaving no microplastics in the soil.
The ambient soil biodegradation tests are currently in progress.

The accelerated disintegration of the Radical Plastics film by the ISO 20200 test method in compositing conditions at 58 °C reported no microplastics by sieving after 3 months of testing.

Film preparation

Based on the small scale compounding and film extrusion campaigns, three initial rolls, 22 microns thick, 21" wide x 600 feet long were produced. One film, called CN20 was based on LDPE resin (low density polyethylene) and was clear. Another film called CN21 had the same formulation as CN20 with the addition of calcium carbonate and carbon black masterbatch. This film, at the 22-micron thickness, was not fully opaque. And the last film called CN22, was a clear film made with a different type of LDPE and is having higher extensibility. All films had the same loading of the same mineral based catalyst and the same inhibitor at the same loading. The compound was made on a 1" Buss kneader at Alphagary, films were blown using a 12" annular die at CharterNEX Films.

The physical properties of these rolls were tested and results are shown in Table 4. It was realized that the films based on the original type of LDPE did not have required tensile strength in the TD direction (transverse direction) and elongation in the machine direction (MD), Table 4. The CN22 film produced acceptable tensile and elongation and this formulation with an increased loading of carbon black and calcium carbonate was used in generation 2 CN24 film. The 1 mil CN24 film still has lower dart impact to be compliant with EN17033. We have addressed this in generation 3 films, but the confirmation is going to be obtained though the 2021 field testing.

Table 4 Physical properties of films:

	Generation	Descriprion	Thickness, um	Tensile strength, MD, MPa	Tensile strength, TD, MPa	Elongation, % MD	Elongation, % TD	Dart, g
ISO17033			>15	>=18	>=16	>=200	>=350	>=100
CN20	1	LDPE clear	22	24.3	12.7	146	434	45
CN21		LDPE black	22	27.3	11.7	115	413	41
CN22		LDPE/LLDPE clear	22	21.1	17.7	435	806	45
CN24	2	LDPE/LLDPEblack	25	27.6	16	200	727	62

Field testing

Field testing of the generation 1 rolls was conducted at a farm in Rio Linda, northern CA and in northern Florida at the University of Florida Institute of Food and Agricultural Sciences (UF/IFAS) in Live Oak, FL. At the University of Florida, Robert Hochmuth, Marina Burani-Arouca, and Dilcia Toro executed the study from soil preparation to harvest using the Syngenta (Bradenton, FL) and Clifton Seed (Faison, NC) watermelon seeds. An industry standard black polyethylene mulch film was compared to the Radical Plastics mulches. Data was collected for watermelon fruit weight and count, volumetric soil moisture content, soil temperature at two depths, and mulch degradability.

Bed Preparation

The experimental area was prepared by rototilling the soil and marking rows that were placed 8 feet apart. The soil was fertilized with 1,000 lbs per acre of a season-long, complete controlled release fertilizer (15-3-21 (N-P_2O_5-K_2O) plus micronutrients) supplied by Harrell's Fertilizer. The fertilizer was incorporated into the soil and the narrow, raised beds were formed. The soil was pressed into a bed 24" wide and 6" tall. After the beds were formed, the hilling discs turned backward were used to "shave" off the outer thirds of the beds to leave a bed 8" wide and 6" tall. Plastic mulch treatments were applied by hand (Fig. 1). This nonstandard bed configuration was used to accommodate the narrow rolls of plastic film supplied by Radical Plastics (21" inch wide). Drip irrigation was installed in the center of the bed in a shallow groove prior to the application of the mulches. Drip irrigation was used to irrigate the crop in all plots.

Figure 1. April 24, 2020, laying plastic mulch film over the pressed bed.

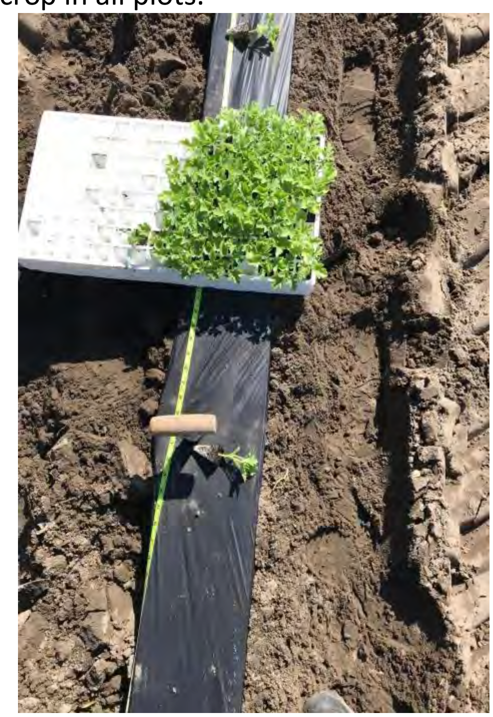

Figure 2. April 24, 2020, Planting water-melon transplants

Seeding and Transplanting

A commonly used standard seeded cultivar, 'Jamboree', was selected for the trial. Transplants were seeded on March 12, 2020 in Speedling (Sun City, FL) 128-cell transplant trays. Transplants were planted in single rows into the beds at a 3-ft spacing on April 24, 2020 (Fig. 2). Each plot was 25 ft in length. The crop was managed for weeds, insects and diseases in accordance with recommended management strategies and no unusual or impactful problems were encountered.

Data collection

Data was collected from April 24 through July 29th, 2020 and included:

- Soil temperature (taken at 3 and 5 inches of depth under the plastic treatments);
- Volumetric soil moisture content (average moisture from the soil surface to 8" in depth using the time domain reflectometry);
- Watermelon yield (count and weight)
- Film degradation rating (10 - complete integrity, 1 – completely degraded

Results

- Raised bed soil temperature is shown in Table 5. At both depths, there are active watermelon roots. Soil temperatures were higher in soil under #20 clear and #22 clear when compared to standard black. Even semi-opaque film #21 had a very similar soil temperature to the commercial PE mulch film.

Table 5. Soil temperatures, North Florida study

Treatment	Plastic Mulch	Soil Temperature (°F)[z]									
		3 in Depth					5 in Depth				
		12-May	2-Jun	24-Jun	17-Jul	29-Jul	12-May	2-Jun	24-Jun	17-Jul	29-Jul
1	#20 clear	103.5 a	89	90.5	87.5	98	95.25	85.5	88	83	93.5
2	#21 black	97 ab	87.5	91	87	95.5	92.5	84.5	87	83	93.5
3	#22 clear	102.5 a	87.5	91.5	87.5	99	94.5	83.5	88.5	84	94
4	Standard black	95.5 b	88	91	85	96.5	90.5	84	88	82	91.5

[z]Values followed by the same letter within a column indicate means are not significantly different ($P \leq 0.05$) with means separation by Tukey-Kramer test. Values followed by notation NS indicate no significant difference between means.

- Volumetric Soil Water Content: Soil under all four treatments held the same amount of moisture throughout this study
- Yield: Conditions were generally favorable for watermelons other than high rainfall totals in June. The planting date was delayed about one month due to COVID-19 restrictions in labor and field work. The total yield was very high, over 70,000 lbs per acre. Fig. 4 shows the yield differences for 3 harvest dates. Radical Plastics mulches matched performance of the standard PE mulch.

Fig. 3 Harvested watermelons harvest

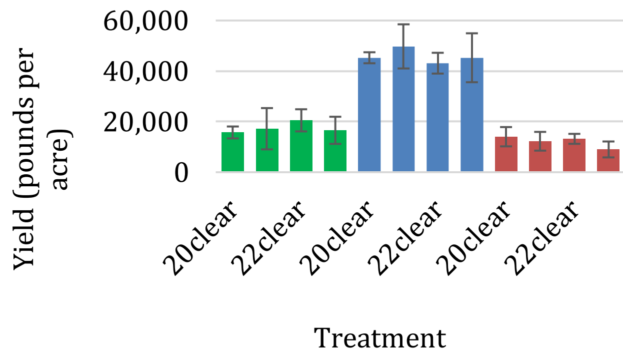

Fig. 4 Fruit weight per treatment per date and error bars (standard error)

- Plastic mulch degradability: Fig. 5 depicts the four plastic mulch treatments on July 29, 2020. At this the date the crop had died and began to expose the plastic. The heat was able to escape degraded areas. The drip irrigation was no longer running. Degradability started to be observed on June 24. On July 29, all three Radical Plastics' mulches had degraded more than the standard black mulch.

CN20 CN22 CN21 Std. PE blk

Fig. 5 Example of each plastic mulch treatment degradation on July 29, 2020, 21 days after final harvest.

The changes of mechanical properties of the same CN21 film aged in CA from April 19 to August 25, 2020 are shown in Table 6 along with non-biodegradable PE mulch film. After 3 mo of its service life, the CN21 demonstrated the initiation of the loss of physical strength and after 4 months was falling apart. The PE control film was still pretty strong after 5 mo of use in the field, when tested side by side with CN21. We could not identify the MD vs TD in aged films and took 5 average readings in both directions.

Table 6 Changes of physical properties of CN21 mulch film used for the onions production in Rio Linda, CA

	Thickness, um	Tensile Stress at Yield (avg) MD, Mpa	Tensile Stress at Yield (avg) TD, Mpa	Elongation, % MD	Elongation, % TD
CN21, not exposed	29.8 and 22.5	16.45	8.12	176	427
CN21, 2 mo CA	28.2 MD, 30.5 TD	16.11	7.2	175	106
CN21, 3 mo CA	29	9.6		26	
CN21, 5 mo CA	difficult to test - almost no strength left				
PE control, not exposed	37	8.85	8.4	288	506
PE control, 5 mo CA	43	7.8		271	

Chemical degradation analysis

The first stage of the degradation required for complete biodegradation is a chemical phase. During environmental exposure, the polymer converts to a more polar, lower molecular weight material. This has been confirmed for both generations 1 and 2 films: the formulations provided 2-4 months delayed chemical conversion based on the thickness of films and geographical location. Mulch films removed from the field were analyzed by IR spectrometry (ATR FTIR, attenuated total reflectance, Fourier-transform infrared spectroscopy) as shown in Fig. 6. There is obvious difference between the unexposed film (lt. blue spectrum) and exposed in the field (grey spectrum). The major difference is in the area of carbonyls (1710-1725 1/cm), hydroxyls (3200-3400 1/cm), ester groups (1400-1100 1/cm).
The non-biodegradable traditional polyethylene mulch film does not change its composition and its IR spectra before and after exposure are identical (Fig. 7).

Fig. 6 also includes the spectra of films accelerated in a Xenon-type weatherometer at different conditions. Only the lower irradiation (0.35W/m2 at 340nm) cycles, programmed as 102min light/18 min dark + spray per ASTM D5071, demonstrated acceptable correlation with natural weathering. The higher energy cycle most likely promoted a different chemical response, e.g. crosslinking, which does not take place at natural outdoors conditions.

The overlay of natural weathering and artificial acceleration by Xenon at 0.35W/m2 at 340nm is shown in Fig. 8. The carbonyl index (CI) is a very sensitive indicator of oxidation and is typically calculated as a ratio of absorption at 1715 (carbonyl peak) to the reference peak at 1465 1/cm (methylene absorption) [1-7]. Fig. 8 demonstrates good correlation and can be used to predict outdoor exposure in MA based on the accelerated weathering testing. We have built similar correlations between the Xenon exposure per ASTM D5071 and CA and FL.

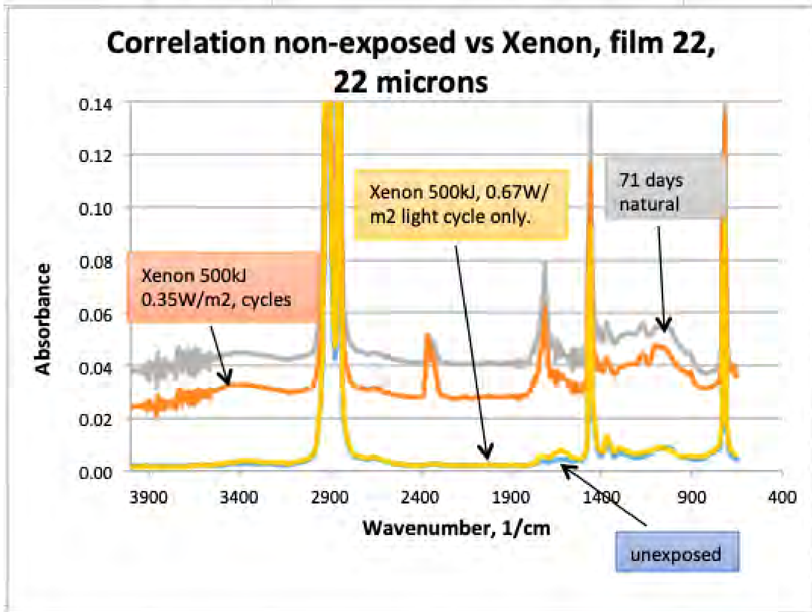

Fig. 6 Change of composition of film CN22 after 71 days of natural exposure in Florida and after accelerated Xenon testing at two conditions: 0.67W/m2 and 0.35 W/m2 irradiation at 340nm

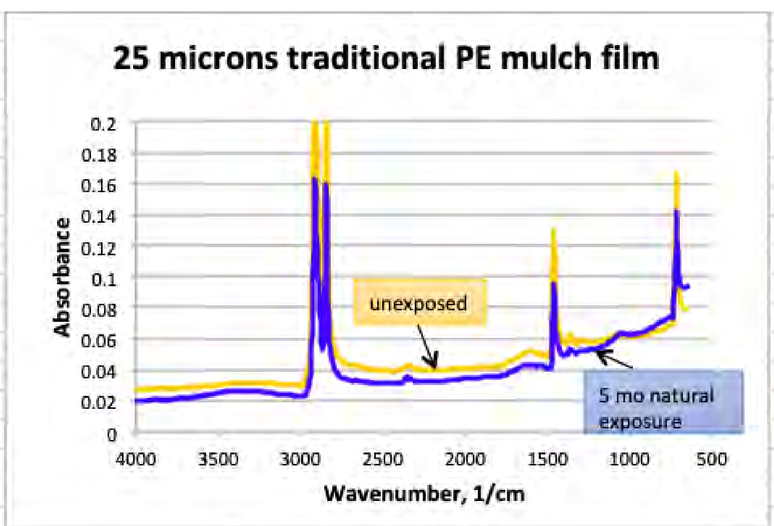

Fig. 7 Non-biodegradable PE mulch film, black, 1 mil thick

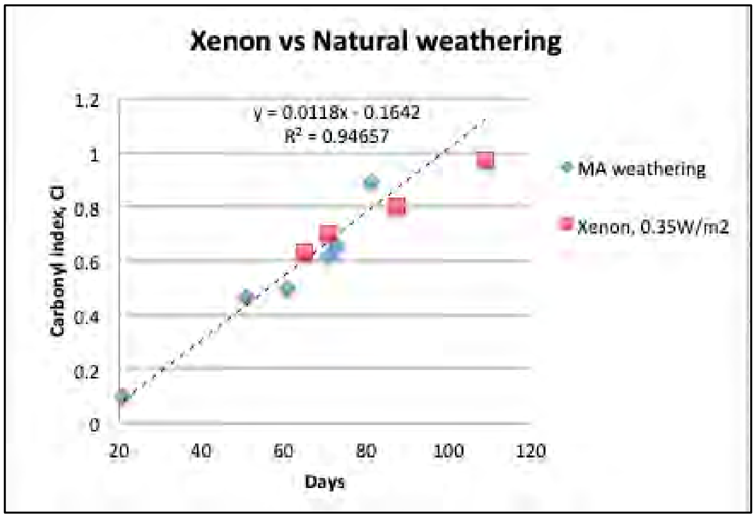

Fig. 8 Correlation of natural and accelerated weathering

Prior to the selection of the specified Xenon based test method, we tested many other accelerating chambers with different light sources and different exposure cycles. They are summarized in Table 7. The fluorescent light based test was done per ASTM D5208-14. The metal halide based Super UV test is developed by Eye Lighting in Japan claiming that polyethylene weathering can be accelerated by a factor of 73 and 120 hours would be equal to a full year of exposure.

All accelerated tests have very different spectral energy distributions, test cycles and produce very different degradation results. The degradation of PE, which exhibits photo-sensitivities to 230, 254, 265, 273, 280, 300 and 331nm wavelengths, cannot be accelerated with light sources which do not produce proportional emissions of these wavelength vs other wavelength of the spectrum. We plan to publish a paper on these findings and recommend a modification to the testing method to the ASTM committee.

We found that only Xenon testing per ASTM D5071 cycle 2 (with light + condensation and dark+ water spray) provides acceptable correlation with natural weathering.

Table 7 Summary of accelerated testing conditions

Accelerated Tests		Irradiance, W/m2 @340nm	Exposure, hrs	Energy, kJs	Black panel temperature, °C	Relative humidity, %	Cycle	Calculated correlation with natural exposure in South Florida	Correlation
			72 and 168		50	50	light only	7 mo and 17 mo	poor
Super UV	Metal halide	4	72 and 168		63	50	6 hrs lt/6 hrs lt+ dk with condensation	7 mo and 17 mo	poor
Qlab, UVCon	Fluorescence	0.89	156	500	63	50	20hrs UV50C/4 hrs dk cond 40C	65 days	poor
			207	500	63	50	light only	2.14 mo	poor
		0.67	310	750	63	50		3.21 mo	poor
			397	500	63	50	102min lt/18 min dk+spray	2.14 mo	good
			596	750	63	50		3.21 mo	good
QSun	Xenon	0.35	794	1000	63	50		4.29 mo	good

Accelerated testing is extremely important as it reduces the film development cycle and provides consistent degradation conditions. The presence of dark and light cycles with hot condensation and cold-water spray, along with irradiation settings matched to the specific geographical area, closely match natural weathering.

Another very important learning from this study, which will be the subject of another technical publications, is that in order to confirm sufficient modification of polyethylenes to undergo biological degradation, calculation of the CI should be conducted on <u>both sides of the exposed film.</u> Currently, based on the reviewed literature [1-7], CI should be >0.4 just on the exposed surface in order to be considered biodegradable. We found that in commercial PE mulch films and oxo-bio films the CI of the exposed side could also reach CI= 0.4, but the chemical modification would be really limited to the first microns of the film surface, keeping the bulk of material unchanged and not readily biodegradable. This confirms the mechanism of microplastics formation. With the Radical Plastics technology, both sides of the film develop CI>0.4 which confirms that the entire film, not just its very thin surface layer, can be biologically digested.

As a part of this study we also confirmed the reduction of molecular weight of the starting polymer by GPC (gel permeation chromatography). The mulch films collected after harvest were dissolved in TCB (1,2,4-trichlorobenzene) solvent and demonstrated a reduction in average molecular weight from 36,000 to 6,090 g/mol which, along with the IR-confirmed chemical changes, satisfies the requirements for initiation of the biological phase of degradation.

Business development activities

1. *<u>Analysis of the Mulch film market</u>:*

   Mulch film is a critical tool for growers and demand is growing. It:
   a. Reduces weeds and labor costs;
   b. Reduces fertilizer usage and associated costs, prevents runoff;
   c. Increases soil temperature, allows for earlier planting;
   d. Increases crop yield and leaves crop cleaner;
   e. Several fruit and vegetable crops are grown “on plastic” – squash, pumpkins, onions, peppers, broccoli, cabbage, tomatoes, melons, strawberries, raspberries, etc.

   Total global market of mulch films is $5B, expected to be $5.7B by 2023.

   In the US, the use of the single use agricultural film exceeds 7 million tons per year and the total addressable mulch film market is almost exactly 1 million acres per year.

The USDA provides data on annual production of each of these crops, split out by state [8]. Figure 9 summarizes data from 2017 by state and crop, with bubble-size proportional to acreage.

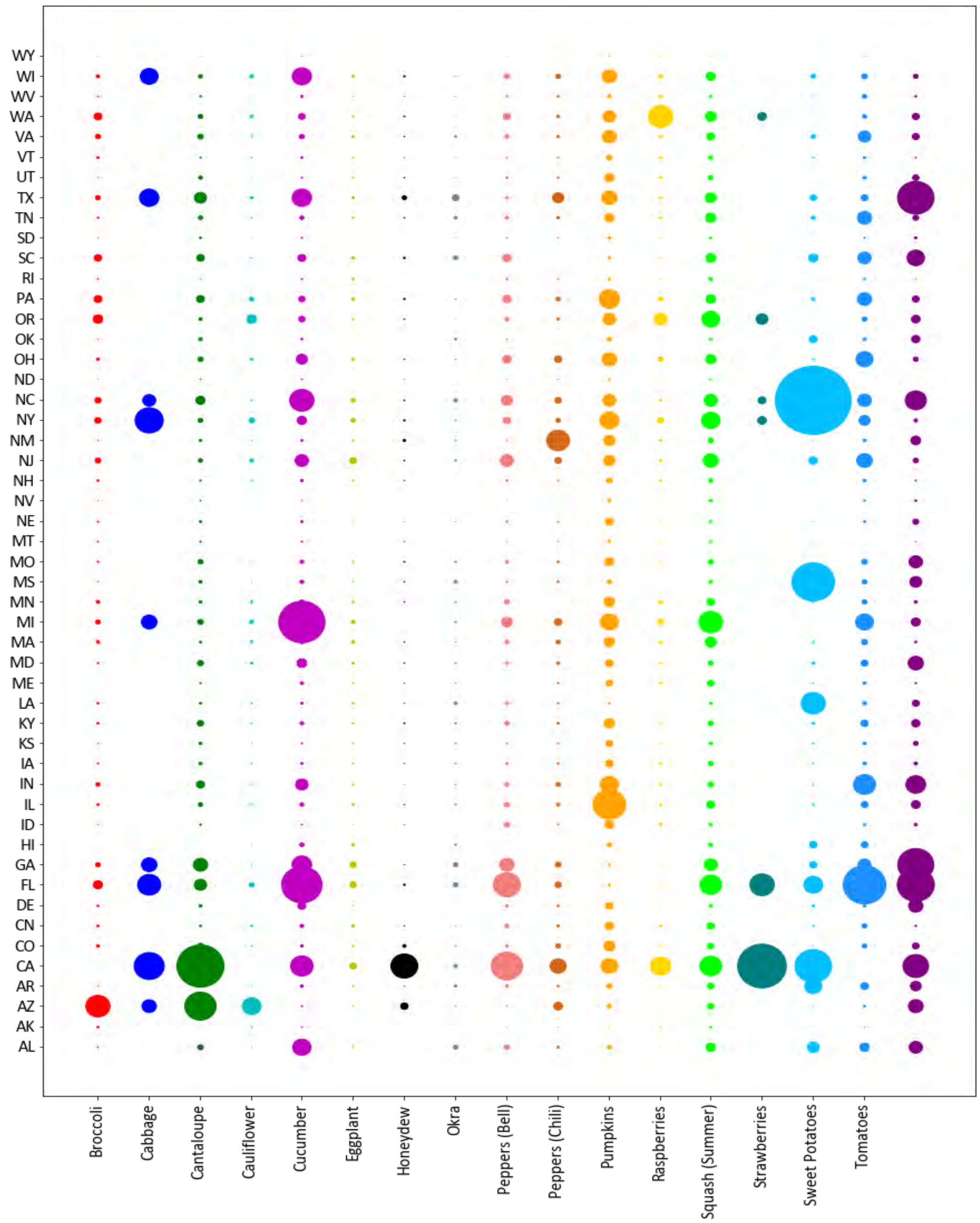

Figure 9: 2017 Data showing distribution of crops by state, with bubble size proportional to acreage

2. *Techno-economic analysis:*

Mulch films are sold by color, thickness and roll size

a. Black mulch film makes up over 80% of the market
b. Custom colors are used for specialty crops (white/black, silver/black, red, green)
c. Typical roll sizes for larger growers: 4’x4000’, 4’x1000’, 5’x4000’
d. Polyethylene mulch is typically 1 – 1.25 mil (25-31 microns)
e. This thickness allows it to be picked up at the end of the season without fragmenting into small pieces
f. 4-6mo growth cycle is confirmed to be applicable to the production of majority of vegetables. After that time, vegetables are harvested and the films can start their biodegradation cycle. Strawberries require 10-11 month before the initiation of biodegradation.

Polyethylene mulch film has 99% of the market, but needs to be collected and disposed of at the end of the season. Typical usage is 2.2 rolls (48”x4000’) per acre, depending on the crop.

Growers would likely switch to biodegradable mulch film if it makes economic sense:

- To avoid labor and disposal costs;
- To prevent topsoil loss;
- To provide a healthier environment for next crop (no plastic fragments in soil or on farm)

3. *Supply chain and distribution:*

Radical Plastics mulch film supply chain is shown in Fig. 10: resin (either bio-based or petroleum based) is procured from resin manufacturers, such as Braskem, ExxonMobil or Dow. The resin is “barefoot” with no additives. Radical Plastics compounds the resin with additives and the catalyst to provide required service life and physical properties. Compound is then converted into film and sent through the distribution to the end user, farmer or industrial grower. The capital light entry point for Radical Plastics technology is compounding or at higher volumes, at the end of the resin manufacturing cycle.

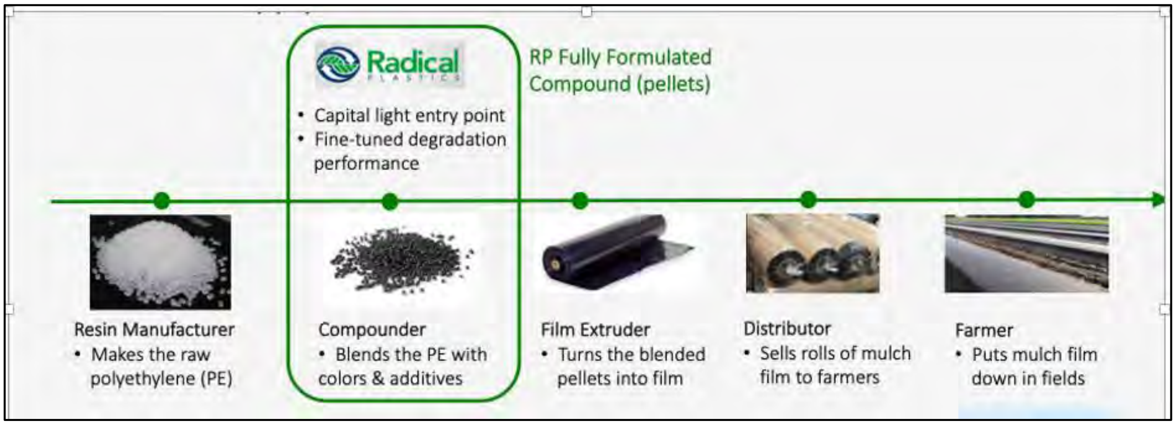

Fig. 10 Radical Plastics supply chain

Referenced literature:

1. E. Chiellini, A. Corti, S. D'Antone, R. Baciu, *Polym Deg.Stab*., 91, 2006, 2730-2747
2. E. Chiellini, A. Corti, S. D'Antone, *Polym Deg.Stab*., 92, 2007, 1378-1383
3. A.Corti, M. Sudhakar, E. CHiellini, *J. Poly Environ.*, 20, 2012, 1007-1018
4. E. Chiellini, A. Corti, G. Swift, *Polym Deg.Stab*., 81, 2003, 341-351
5. I. Jakubowizc, *Polym Deg.Stab*, 80, 2003, 39-43
6. M.M. Reddy, M. Deighton, R. Gupta, S.N. Bhattacharya, R. Parthasarathy, *J. Appl. Polym. Sci*, v111, 2008, 1426-1432
7. I. Kyrikou, D. Briassoulis, M. Hiskakis, *Polym Deg.Stab*., 96, 2011, 2237-2252
8. USDA NASS. 2017. https://www.nass.usda.gov/index.php.