Interim Report – Year 1

SERDP-WP21-3053

Electrospun Multifunctional Composite Fibers for Improved Warfighter Insect Protection

29 April 2022

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14. ABSTRACT

We report on progress from the first year of a 3-year program (SERDP WP21-3053) to develop novel insect repellent fibers and fabrics using electrospinning as a rapid prototyping technique to evaluate composite multifunctional fiber designs containing dual environmentally friendly insect repellents (dual combinations of picaridin, DEET, or permethrin) for their controlled delivery.

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Abbreviations

ARL	Army Research Laboratory
ATR-FTIR	Attenuated Total Reflectance Fourier Transform Infrared
DEET	*N*,*N*-Diethyl-*meta*-toluamide
DSC	Differential Scanning Calorimetry
E_a	Activation Energy
FA	Formic Acid
GC-MS	Gas Chromatograph / Mass Spectroscopy
IR	Infrared
NECE	Navy Entomology Center of Excellence
NRL─DC	Naval Research Laboratory, Washington D.C.
rel. wt%	Weight percent relative to polymer mass
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
wt%	Weight Percent

Keywords

Electrospinning, fibers, insect repellents, multifunctional composites, electrospun yarn

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1. Executive Summary

1.1. Introduction and Objectives

We report on progress from the first year of a 3-year program (SERDP WP21-3053) to develop novel insect repellent fibers and fabrics using electrospinning as a rapid prototyping technique to evaluate composite multifunctional fiber designs containing dual environmentally friendly insect repellents (dual combinations of picaridin, DEET, or permethrin) for their controlled delivery. Electrospinning was used to fabricate nanofibers and from multiple series of mixed insect repellent nylon fiber composites, including mixtures of DEET, picaridin, and permethrin at various loading ratios. The repellents were encapsulated within the polymer network in monofilament nanofibers, or within the core of core/sheath nanofibers. We have identified preliminary effects of electrospinning parameters, such as distance to collector, polymer/repellent concentration, and relative flow rates, on fiber morphology and repellent release dynamics. Thermal analysis, including isothermal TGA, was used to determine repellent loading levels and release rates. We quantify the insect repellent release kinetics from the composite fibers and extrapolate to predict half-live and efficacy lifetime at ambient temperatures. The insect repellency of down-selected candidates will be assessed against live mosquitos using a push test method. We discuss the role of relative loading concentration, and synergistic effects on insect repellency and fiber morphology, as well as identify structure property relationships to facilitate continued development into yarns and fabrics. The scope of this effort encompasses first electrospinning as a rapid prototyping method to identify fiber designs that exhibit effective repellency against live insects, and then the demonstration of their fabrication with conventional, scale-able fiber drawing techniques to facilitate transition

1.2. Technical Approach

Electrospinning was employed to physically embed active additives into textile fibers to improve retention of their functional properties while maintaining the physical performance of traditional fabric. Monofilament and coaxial electrospinning afford the ability to create hierarchically-structured functional micro- to nano-scale fibers by controlling the composition of specific areas of the fiber (core vs. surface). This is critical for the insect repellent application in which the release should occur slowly throughout the lifetime of the garments.

In this period, nylon electrospun fibers containing single and dual insect repellents (picaridin and DEET) were fabricated and evaluated for complementary release profiles and synergistic enhancement of repellency. Additionally, electrospun fibers were physically twisted into yarns and threads to evaluate feasibility for direct scale-up of design concepts, such as one potential path conceptualized in Figure 1.

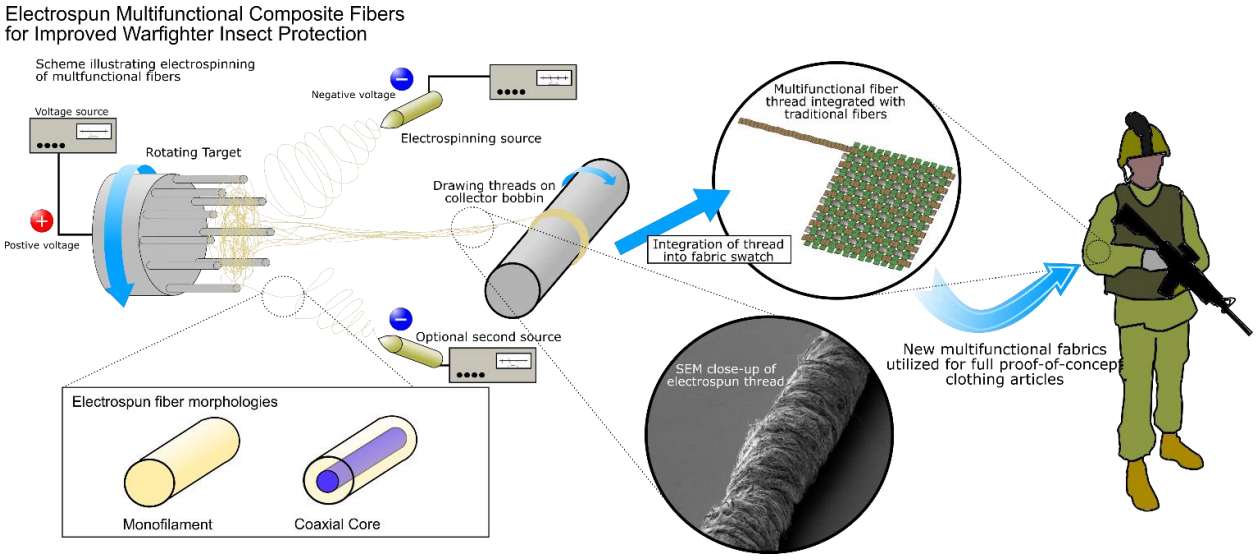

Figure 1. Conceptualization of direct development path of monofilament and coaxial electrospun fibers to functional webs, patches, and potentially textiles.

Nylon has been the primary polymer used to date since it is currently used in uniform

fabrics, thereby facilitating smoother transition into the supply stream. Further, the electrospinning parameters for Nylon are well documented by NRL in recent literature.[1] Additional polymers, including polypropylene and polyethylene terephthalate, are planned subjects of future evaluation.

Electrospinning is a facile lab-scale method to rapidly assess various fiber composite designs (Figure 2). Here, we employed electrospinning to fabricate composite fibers containing two different insect repellents, i.e. DEET and picaridin, in a single fiber. Based on SEM images of each of the monofilament Nylon/DEET and Nylon/Picaridin composites in the previous Limited Scope effort, it was expected that utilizing a mixed repellent system would result in fiber morphologies similar to that of the neat composites, but with tunable fiber composition and release profiles. Furthermore, the release profiles of insect repellents with different vapor pressure could be tuned to enable complementary release profiles to leverage potential synergistic effects in repellency.

To enable potential transition for textile applications, this work uses only previously approved insect repellents and consults published toxicity information to determine loading concentration limits of additives. Picaridin (1-(1-methylpropoxycarbonyl)-2-(2-hydroxyethyl)piperidine) and *N*,*N*-Diethyl-*meta*-toluamide (DEET) were incorporated at several relative concentrations within a single fiber.

For the different deposition compositions, the fibers' structure are characterized using the experimental techniques described in Section 0-Materials and Methods to determine the optimal conditions to achieve uniform and aligned fibers. The mechanical properties were also evaluated as a function of insect repellent loading to identify effects of repellent loading on mechanical properties. Next steps will involve the efficacy evaluation against live mosquitos at the Navy Entomology Center of Excellence (NECE). This work is currently on-going and will inform the

near-term direction of fiber design selection for transition to extrusion techniques.

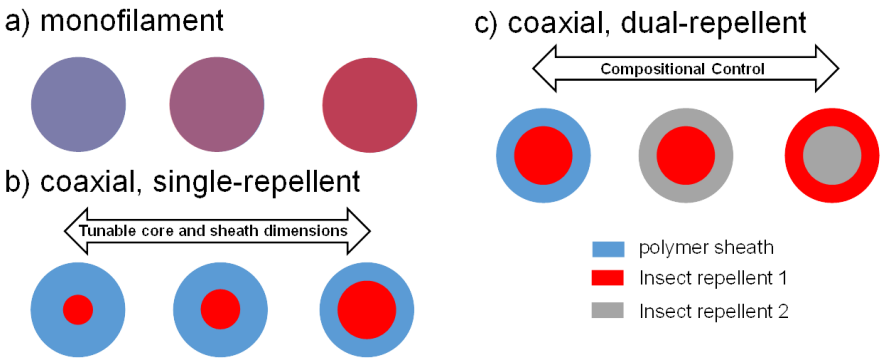

Figure 2. Cross-section of fiber structures demonstrating conceptual approach to controlled release rate and optimize lifetime: a) monofilament fibers of increasing insect repellent composition; b) coaxial fibers of increasing core dimension; and c) coaxial fibers composed of dual repellent solutions.

1.3. Results

This report details the significant progress made in four focus areas: DEET-loaded electrospun nylon fibers, Permethrin-loaded electrospun nylon fibers, dual repellent (DEET/Picaridin) electrospun nylon fibers, and preliminary electrospun yarns. Results on each are briefly summarized here and further detailed in the subsequent chapters.

DEET fibers. Electrospun nylon fibers with incorporated DEET were fabricated and were shown to retain ca. 80% of the initial amount of repellent. Incorporation of up to 50 rel. wt% DEET relative to nylon has no detrimental effect on fiber morphology. It was shown that the effective lifetime was dependent on the amount of sample (i.e. the weight) and the concentration of nylon. For samples akin to ultra-lightweight fabric, it was estimated that DEET repellency would be active for > 72 hours which far outperforms common topical application.

Permethrin fibers. We demonstrate success in incorporating Permethrin up to 10 rel. wt% in electrospun nylon fibers. The morphology of the fibers was unaffected by Permethrin loading

and thermal properties largely maintained. This preliminary evaluation demonstrates the potential to incorporate permethrin into electrospun nylon fibers at relatively high loading concentrations.

Dual Repellent Fibers. We designed and fabricated dual repellent nylon electrospun fibers containing both DEET and Picaridin at several ratios. Both repellents were successfully incorporated into the nylon fibers, with slightly more Picaridin retained than DEET. All formulations exhibited very long half-lives, with 75:25 DEET/Picaridin exhibiting a particularly long half-life that was attributed to potential synergistic effects.

Preliminary electrospun yarns. Preliminary electrospun yarns were produced from the insect repellent-loaded nylon electrospun fibers. The individual nanofibers were retained when incorporated into individual filaments and maintained their morphology throughout the twisting process. The yarn was ca. 150 μm in diameter, which is comparable to commercially available polymer filaments used in conventional fabric manufacturing. The electrospun insect repellent nylon fibers proved compatible with mechanical yarn fabrication techniques.

1.4. Benefits

Electrospinning affords low material requirements and flexible processing controls that enables the rapid evaluation of new fiber designs, which then can be applied to conventional fiber drawing techniques (e.g. melt extrusion) for demonstration of scale-up potential. The encapsulation of insect repellent (i.e. picaridin, DEET) into textile fibers via a bottom-up approach affords the potential to create fabrics and garments that offer long-term protection to the warfighter from insect-borne diseases. Incorporation of the active materials into fibers will greatly enhance the durability of these functionalities to laundering, especially when compared with surface treatments, strongly reducing the current health hazards present for surface treated fibers and

increasing their environmental sustainability. The insect repellent fibers that will result from this program have the potential to greatly reduce environmental and health risks during their lifecycle by 1) increasing the longevity of functionalities after laundering, 2) reducing direct skin contact of active additives by encapsulation within the core of a benign material, and 3) generating novel fibers from which textiles and garments could be intelligently designed with functionalities localized and limited only to the areas in which they are needed.

Results and progress from this reporting period present multiple potential beneficial applications. The insect repellent electrospun fibers are fabricated in non-woven mats, which can be directly employed as repellent patches, cuffs, wipes, or clothes. The current status of the material fabrication is immediately compatible with such applications. Pre-loaded insect repellent fibers offer benefits including eliminating application by user, eliminating potential exposure to excess vapor to the user, and importantly sustained release. The fiber designs discussed herein exhibit significantly longer half-lives of release than current commercial insect repellent products, and thus represent an immediate dramatic improvement in the effective repellent lifetime.

2. Background

Mosquitoes are a common vector for the transmission of a number of diseases such as Malaria, Zika and Yellow Fever. Of these, malaria is a significant source societal burden in areas where it is endemic. According to the WHO, there were an estimated 241 million cases of malaria in 2020 resulting in 627,000 fatalities, 80% of which were children under the age of five.[2] Vector control, consisting of insecticide-treated nets and indoor residual spray are the most effective ways of reducing transmission. Personal use of insect repellents is a simple, yet effective method of preventing insect-borne disease.

The performance requirements and technical strategies for imparting insect repellency on a fabric are quite different than other functionalities, such as flame retardancy. Current practices for the prevention of contact and bites and related infections from mosquitoes, midges, flies, fleas, and ticks comprise a repellent and insecticide combination, generally applied to the skin and textiles, respectively. The most common cloth applied repellent are N, N-diethyl-3-methylbenzamide (DEET), originally developed in the 1940's,[3] and permethrin, a broad spectrum, non-systemic synthetic pyrethroid.[4] Permethrin, as well as other pyrethroids, disable the nervous system of insects by interrupting sodium ion flow in axonal membranes, ultimately resulting in paralysis and death of the target organism. Due to the specificity of this mode of action, and the difference in comparable mammalian systems, permethrin has very limited effects on humans and is therefore approved for large-scale use on most populations. However, permethrin is highly toxic to aquatic invertebrates, fish, and honeybees. Picaridin (1-(1-Methylpropoxycarbonyl)-2-(2-hydroxyethyl)piperidine, also known as Icaridin) is an effective repellent compound with performance comparable to DEET, and does not exhibit potential for skin irritation.[5] Further, while DEET is often sprayed onto clothing, it is not considered a durable repellent resulting from

such topical applications. Fibers treated with picaridin have been shown to be more effective than those treated with DEET to repel insects from untreated underlying skin.[6] IR-3535 (ethyl butylacetylaminopropionate) is a synthetic amino acid that interacts with the chemical receptors of insects. IR-3535 is applied directly to the skin and has been widely used in Europe over the last few decades exhibiting similar performance as picardin.[4]

Researchers have turned towards repellent encapsulation within a polymeric material to address these issues. Encapsulation has proven an effective method of both limiting direct contact between repellent and skin, as well as extending the lifetime of repellency.[7] Encapsulation within a polymeric network has been shown to be an effective strategy for limiting the evaporation and thus increasing the lifetime of DEET. Researchers have successfully used extrusion compounding[8], melt spinning[9], and microencapsulation[10-12] to suppress DEET evaporation and significantly increase the lifetime of repellency.

Another promising method is electrospinning, which is a facile method of fabricating polymeric nanofibers. During the electrospinning process, high voltage is applied to a needle tip through which is pumped a polymer solution. As the charged solution is accelerated towards a grounded collector plate, the solvent is evaporated and the polymer jet stretches to form a nonwoven mat of polymeric nano- or micro-fibers. Electrospinning is a facile, and versatile method to achieve polymeric nanofibers with varying morphologies such as core/sheath[13-15], beads[16], mesoporous.[17] Likewise, electrospinning is a popular way of encapsulating a target molecule within a polymer matrix. Electrospinning has been used to fabricate fibers containing a variety of repellents/insecticides such as icaridin[18], and permethrin.[19] Additionally, DEET was successfully incorporated into electrospun nanofibers made from a multicomponent, cyclodexrin-based polymer[20] as well as poly(l-lactic acid)[21], but the former involves multistep polymer

synthesis and characterization of the repellent release rate was not performed in the latter.

3. Materials & Methods

Materials. Nylon 6/6 (nylon) was obtained from Aldrich, N,N-diethyl-m-toluamide (DEET) was provided from TCI America, and Formic acid (88%) was provided by Fisher Scientific. All materials were used as received.

Solution Preparation. Nylon solutions were prepared by adding nylon beads to a solution of formic acid in a 10 dram vial to achieve the desired concentration (12.5 – 18.0 wt%). To this was added DEET to achieve the appropriate ratio with respect to nylon (0 – 50 rel. wt%). The solution was sealed and heated to 50 °C overnight in a block heater to completely dissolve the contents. Sealed solutions were kept at 2 – 4 °C and allowed to warm to room temperature before electrospinning.

Electrospinning. Monofilament electrospinning was performed on a custom-built system using a New Era Pump Systems syringe pump (NE-300) oriented horizontally towards a grounded collector. The electrospinning solution was loaded into a 5 mL syringe with a 22 gauge needle. Fibers were electrospun at a flow rate of 0.9 $mL \bullet hr^{-1}$, a temperature of 20 – 22 °C, and a relative humidity of < 35%. The needle was set at distance of 12 cm away from the collector horizontally and the voltage between the needle and collector was set to 15 kV by a Bertan Series 205B high voltage power supply. Under these conditions, non-woven mats were generated at an approximate rate of 100 mg/hr. Fibers were collected onto aluminum foil, glass slide, or SEM post and were analyzed within 24 hours of electrospinning.

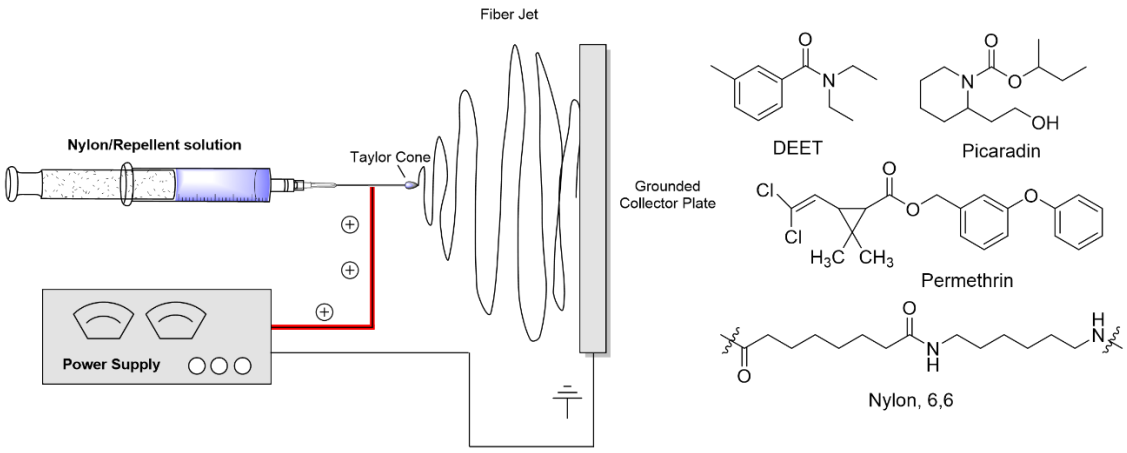

Figure 3. (Left) A general depiction of an electrospinning setup. High voltage is applied to a needle tip through which a nylon/repellent solution is pumped. At the taylor cone formed at the needle tip, the solvent evaporates as the polymer jet accelerates towards the collector plate. The result is a non-woven mat of polymeric nanofibers. (Right) The chemical structures of common insect repellents and nylon 6,6.

Thermal Analysis. Analysis of release kinetics and fiber composition was characterized by thermogravimetric analysis (TGA) on a TA Instruments Discovery TGA using platinum pans (100 µL). Heating ramps were performed at a heating rate of 10 °C•min^{-1} to 600 °C. For kinetic measurements, isothermal decay curves were performed in a nitrogen atmosphere at 60, 80 and 100 °C for 300 min. Isothermal curves were fit to non-linear decay models using Origin software. Low-temperature DSC was performed on a DSC Q100 V9 measuring from -120 °C to 60 °C. The sample was cooled from room temperature to -120 °C at a rate of 10 °C•min^{-1} before heating to 60 °C at the same rate. All thermal analyses were performed in triplicate.

Scanning Electron Microscopy (SEM). SEM was performed on a JEOL JSM-7600F field emission scanning electron microscope (Peabody, MA) operated at an accelerating voltage of 5 kV. Samples were sputter-coated with least 3 nm gold prior to SEM analysis using a Cressington 108 autosputter coater equipped with an MTM20 thickness controller. ImageJ software was utilized to measure fiber sizes from the SEM images ($n \geq 100$).

Headspace sampling, analysis, and method. To detect and identify the volatile organic compounds (VOCs) that evolve from Nylon/DEET fibers, a 7890B/5977B Agilent GC-MS coupled with the 7697A Agilent Headspace Sampler (Agilent Technologies, Santa Clara, CA) was used for analysis. The GC-MS was equipped with a 30 m x 0.25 mm i.d. x 0.25 mm, Rxi-5MS column (Restek, Bellefonte, PA). The headspace was generated by fabricating 18% nylon with 50% rel. wt DEET monofilament fibers via electrospinning as previously described. Approximately 2 mg of fibers were rolled into a ball, and placed into a 20 mL Agilent headspace vial equipped with a crimp cap. The fibers were allowed to sit at room temperature (22 °C ± 3°) for 5 days. Prior to headspace extraction, the vial was allowed to equilibrate at 90 °C for 25 min while shaking at 50 shakes/min in the headspace sampler. Followed by 30 s injection to the injection loop set at 90 °C. The sample was transferred to GC-MS via transfer line set to 100 °C, the analytes flowed at a rate of 20 mL/min with a 10:1 split. The GC column oven began at 40 °C, was held for 30 s, increased to 250 °C at 40 °C•min^{-1}, and finally held at 250 °C for 1 min. The mass scan range m/z 40-300 and the transfer line to the MS was 250 °C. DEET was the only compound within the headspace and was preliminarily identified by matching to the NIST Spectral Library and by comparison to a neat DEET sample. All analyses were performed in triplicate.

Mechanical analysis. Electrospun mats were fabricated by electrospinning onto a target for 150 minutes. The fibrous mats were cut into 1 cm x 5 cm strips and tested using an Instron 345C-1 equipped with 50 N load cell and pneumatic grips at 10 mm•min-1. Neat nylon fibrous mats were electrospun from solutions containing 12.5, 14.0, or 16.0 wt% nylon in formic acid. For samples containing DEET, the electrospun solution contained 50 rel. wt% DEET relative to the concentration of nylon. Error bars are the result of $n \geq 5$ measurements. All mechanical analyses were performed in triplicate.

4. Results and Discussion: Task 1 - DEET Fibers

In order to develop an effective encapsulation strategy, the release rate, protection time, product stability, ease of processing, and cost of formulation all must be considered. In this section, we demonstrate a simple method for the fabrication of electrospun nanofibers and nanofibrous mats of made up of a commercially available polymer, nylon 6/6, with encapsulated DEET for extended release profiles. We show that the DEET is incorporated within the polymer matrix and the evaporation is limited such that the active lifetime of DEET is significantly increased relative to topical application. The effect of the polymer and repellent concentration on the fiber morphology is investigated and the release rate and mechanism of DEET from the polymeric nanofibers is explored.

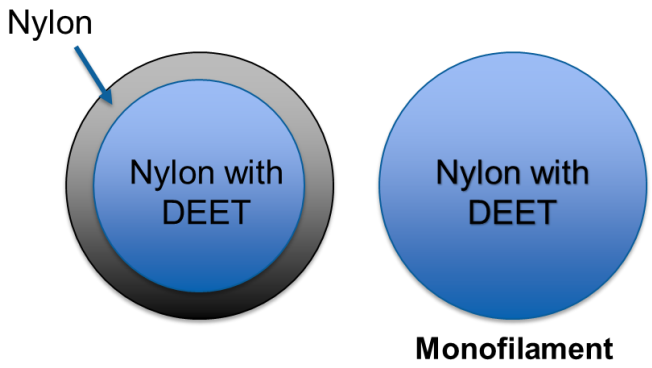

Figure 4. Cross-section of composite DEET-nylon fibers of coaxial (left) and monofilament (right) designs.

4.1. Motivation for DEET fibers.

There are many commercially available repellents that are composed of natural oils, citronella, and more, but *N*,*N*,-diethyl-meta-toluamide (DEET) has been established as one of the oldest and most effective options. Seen as the "gold standard" for insect repellent, DEET is popular due it's long lifetime, low toxicity and low cost.[22] Despite its widespread use, the mechanism of

DEET repellency is not currently well-understood, however, a study by Reifenrath and Robinson established a correlation between the evaporation rate and the repellency of DEET noting that a minimum evaporation rate of 2.6 $\mu g \bullet cm^{-2} \bullet hr^{-1}$ is necessary for DEET to be effective.[23] Furthermore, there is evidence that DEET is multifunctional, acting by direct insect contact in addition to acting as a spatial repellent.[24-25] Although DEET is generally considered safe[26], concerns about skin permeability[27-28], especially in children[29], and during pregnancy[30], have driven research towards alternative, non-contact, methods of repellent delivery. Furthermore, topical repellents often lack long lifetimes and require frequent re-application in order to remain effective. Current commercial formulations contain up to 30 wt% DEET and only offer up to 6 hours of protection.[31] Therefore, there is a need to both sequester the DEET to prevent absorption into the skin as well as limit evaporation to increase its effective lifetime.

4.2. Monofilament DEET fiber morphology.

To fabricate repellent-loaded nanofibers, solutions containing nylon and DEET in formic acid were electrospun. Previously, it has been shown in systems using poly(l-lactic acid) that DEET can be incorporated at concentrations >50 rel. wt%, however, the resultant fibers had significant defects and unfavorable microstructure formation due to the phase behavior of the electrospinning solutions.[21] To fabricate nylon fibers incorporating repellent, solutions of 12.5% nylon 6/6 in formic acid were prepared with 0, 10, 30 and 50 rel. wt% DEET relative to nylon (rel. wt%).

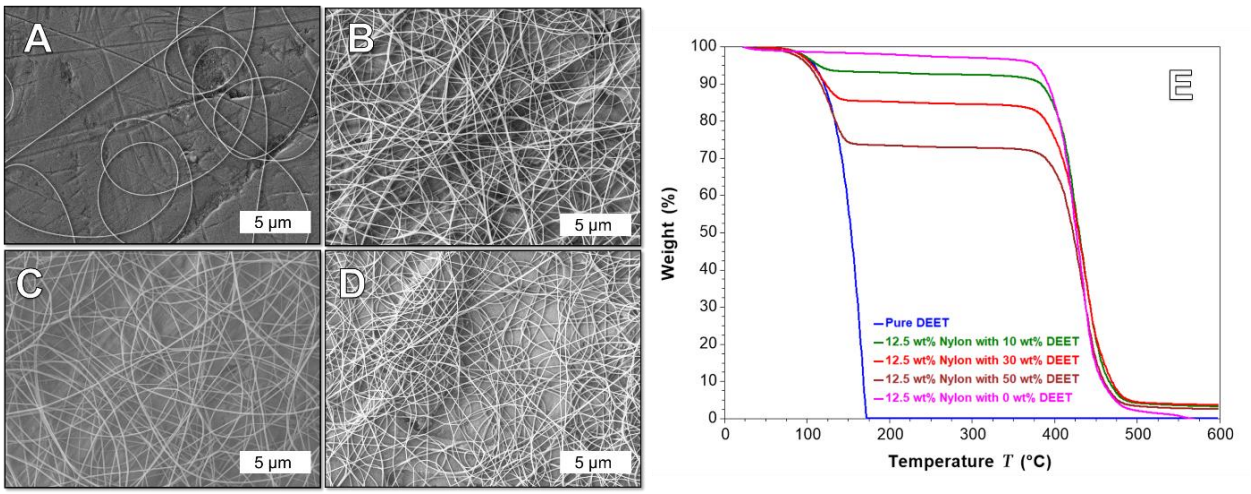

Figure 5. SEM images of electrospun nylon nanofibers fabricated from solutions containing 12.5% nylon in formic acid and 0 (A), 10 (B), 30 (C), and 50 (D) rel. wt% DEET, respectively. (E) Thermal analysis showing the mass loss when heating pure DEET, and electrospun fibers with 0 – 50 rel. wt% DEET, up to 600 °C.

As shown in Figure 5 A-D, fiber morphology was investigated by SEM and uniform, cylindrical fibers were obtained at repellent loadings of up 50 rel. wt% DEET. The presence of DEET had a small effect on fiber diameter, with fibers fabricated with > 30 rel. wt% DEET exhibiting larger diameters than those fabricated at lower concentrations suggesting there may be minor polymer swelling at higher repellent loadings. Significantly, the presence of DEET at up to 50 rel. wt% had no detrimental effect on fiber morphology.

The composition of electrospun fibers was investigated using TGA heating ramps. Fiber samples were heated from room temperature to 600 °C at a rate of 10 °C•min^{-1} (Figure 5E). This allows the residual DEET concentration in the fibers after electrospinning to be quantified. In the absence of DEET (0 rel. wt%), there is little mass loss at ca. 100 °C which confirms the lack of DEET and further indicates no residual formic acid in the electrospun fibers. As the concentration of DEET in the electrospinning solution increases, there is a corresponding increase in the mass loss at ca. 100 °C. Concurrently, no formic acid was detected in the headspace of DEET-loaded fibers. Therefore, the initial loss of mass in DEET containing fibers may be attributed to small

amounts of DEET residing on the surface of the fibers and correspondingly quick, low temperature release. The thermal stability of the nylon fibers were unaffected by DEET loading, as all fibers were stable up to 400 °C before thermal polymer decomposition. This suggests that DEET is physically incorporated in the polymer matrix and does not indicate chemical interactions with the polymer backbone. Fiber diameters and retention of DEET in the electrospun fibers are shown in Table 1.

Table 1. The retention of DEET in electrospun nylon nanofibers.

[DEET], wt %[A]	Fiber Diameter, nm	Mass loss, wt%[B]	Retention DEET, wt %
0.0	110 ± 30	2.04	-
10.0	113 ± 17	6.92	76.1
30.0	164 ± 22	14.8	69.1
50.0	186 ± 23	26.5	79.5

[A] Initial loading relative to nylon. All samples prepared with 12.5 % nylon 6/6 in formic acid. [B] Measured at 200 °C.

The amount of DEET retained was determined by the mass loss at 200 °C, a sufficiently high temperature to ensure complete evaporation of repellent. After electrospinning, the fibers retained up to 79.5% of the DEET present in the electrospinning solution. There was no significant change in DEET retention with respect to the initial DEET concentration suggesting that the final loading was dependent only on evaporation during electrospinning.

To gain insight into the incorporation of DEET within the polymeric nanofibers, the glass transition temperature (T_g) of DEET-loaded nanofibers fabricated from a solution containing 12.5% nylon and 50 rel. wt% DEET was analyzed using low temperature DSC. The T_g of pure DEET was -77.8 °C, which is consistent with previous results.[32] However, the DEET present in

the electrospun nanofibers, had a modest increase in T_g to -70.4 °C, suggesting that there is a strong interaction between DEET and the polymer matrix. Importantly, a higher T_g also indicates that DEET is well dispersed in the nylon matrix and does not exist in a distinct phase within the fibers. Furthermore, headspace analysis performed by GC/MS detected DEET in the headspace above a sample of nylon/DEET nanofibers. This further confirms that DEET is incorporated into the polymer network but, importantly, demonstrates that DEET also freely evolves from the nanofibers and the nylon-DEET interactions do not inhibit its release.

4.3. Monofilament fibers with varying concentrations of nylon.

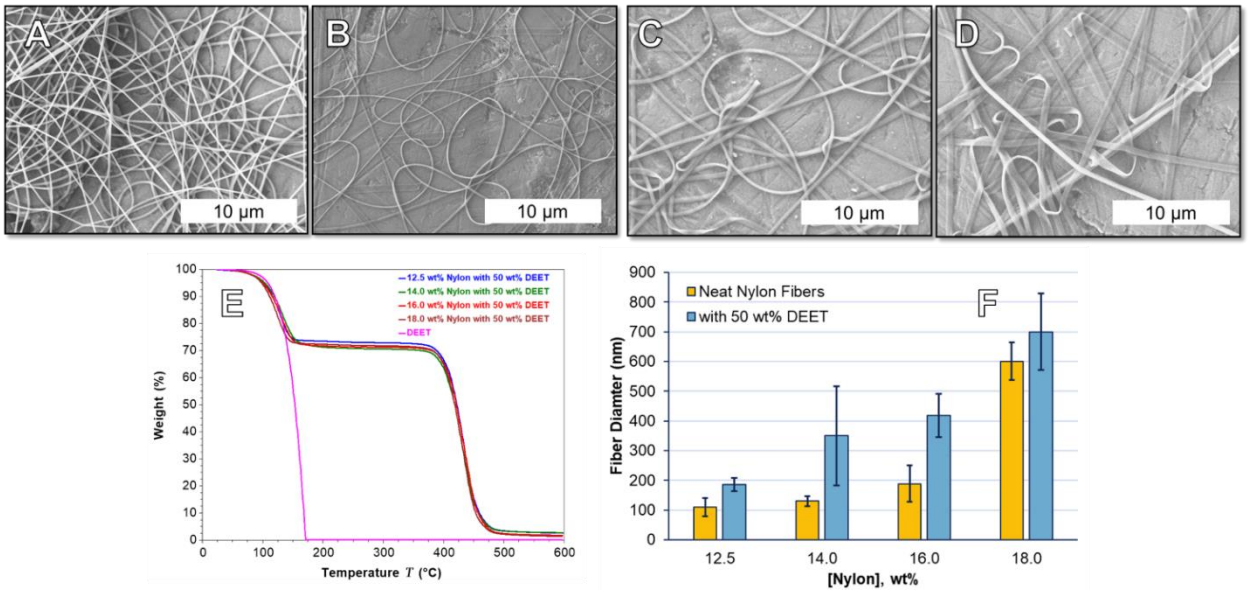

Figure 6. SEM images of electrospun nylon nanofibers fabricated from solutions containing (A) 12.5, (B) 14.0, (C) 16.0 and (D) 18.0 wt% nylon in formic acid and 50 rel. wt% DEET, respectively. (E) TGA heating ramp showing the mass loss of pure DEET, and electrospun fibers with 12.5 – 18.0 wt% nylon and 50 rel. wt% DEET. (F) As the concentration of nylon is increased, there is a corresponding increase in the fiber diameter due to the formation of flat, ribbon-like fibers at higher concentrations. There is also an increase in the fiber diameter when 50 rel. wt% DEET is added into the electrospinning solution.

After determining that incorporation of DEET at 50 rel. wt% had no significant effect on the fiber morphology in 12.5 wt% nylon fibers, the effect of nylon concentration was investigated

for samples made with 50 rel. wt% DEET. Monofilament nylon fibers were electrospun from formic acid solutions containing 12.5, 14.0, 16.0, and 18.0 wt% nylon. The effect of the nylon concentration on fiber morphology was investigated by SEM (Figure 6A-D). At concentrations up to 16.0 wt%, nylon concentration had no significant effect on the fiber diameter as nylon fibers displayed uniform cylindrical morphology with a fiber diameter of ca. 200 nm. However, at 18.0 wt%, the fibers were flattened into ribbon-like morphology with a corresponding fiber diameter of ca. 600 nm. Ribbons are commonly observed in electrospun polymer solutions using a volatile solvent and have been attributed to the formation of a thin skin layer during the electrospinning process and subsequent collapse of the thin-walled nanofiber as it is unable to support the increase in fiber diameter.[33] Indeed, ribbons have also been previously observed in electrospun nylon 11 nanofibers as a function of concentration.[34] Therefore, it is proposed that at high nylon concentrations, rapid evaporation of formic acid from the polymer jet during electrospinning is initially localized to the surface and results in a skin formation at a larger fiber diameter. Subsequent evaporation from the bulk through the skin then causes partial collapse of the fiber into the ribbon morphology.

Table 2. The effect of the concentration of Nylon on the fiber morphology.

[Nylon], wt %[A]	Fiber Diameter, nm	Mass loss, wt%[B]	Retention DEET, wt %
12.5	186 ± 23	26.5	79.5
14.0	350 ± 167	29.2	88.5
16.0	418 ± 73	28.6	86.7
18.0	700 ± 129	28.0	84.8

[A]All samples made with 50 wt% DEET relative to nylon. [B] Measured at 200 °C.

In fibers loaded with 50 rel. wt% DEET, thermal analysis shows that increasing the nylon concentration has a negligible effect on the DEET release temperature, DEET retention, or the degradation temperature of the nylon (Figure 6E). The addition of DEET led to a measureable increase in the fiber diameter for all concentrations of nylon when compared with neat samples (Figure 6F). As the concentration of nylon was increased, there was a modest increase in the retention of DEET, as well. Therefore, fiber diameter is marginally dependent on both DEET and nylon concentrations. Increasing the nylon concentration may cause an increase in the chain entanglements of DEET in solution resulting in a higher DEET concentration in the final fibers. Interestingly, the fiber morphology followed a similar pattern with the fibers made at > 14.0 wt% nylon displaying ribbon-like morphology and those made a lower concentrations remaining cylindrical. Furthermore, fibers with ribbon-like morphology displayed similar retention rates to those with cylindrical morphology. Other than a swelling of the nanofibers leading to a larger diameter, there is no significant effect of the addition of DEET on the electrospun nanofibers at different nylon concentrations. As such, electrospinning from more concentrated nylon solutions has potential to decrease the amount of solvent used in the fabrication process and reduce potential environmental considerations.

4.4. Release rate and active lifetime of repellent in DEET-nylon nanofibers.

The effect of nylon concentration on the release rate for samples fabricated with 50 rel. wt% DEET was measured using isothermal TGA at multiple temperatures. To determine the release rate of DEET from nylon fibers at ambient temperature (20 °C), the release profiles were captured using a series of isothermal TGA experiments at 60, 80 and 100 °C. To perform the isothermal experiments, the system is held at the desired temperature for 5 h and the mass loss is

attributed to the evaporation of DEET from the nylon nanofibers over time. The data were fit using a first-order reaction model (eq. 1) to determine the rate constant (k) for the reaction and the temperature dependence of the rate constant was used to calculate the activation energy (E_a) using the Arrhenius equation (eq. 2). From the activation energy, the rate constant for DEET release at 20 °C was calculated using eq. 2 and the half-life for a first-order process can be calculated using eq. 3.

$$(1) \quad y = A * e^{-kt} + c$$

where y is the mass percent remaining of the sample for a given temperature at time, t. A is defined as a pre-exponential factor, k, is the rate constant, and c is a constant for fitting purposes.

$$(2) \quad \ln(k) = \frac{-E_a}{RT} + \ln(A)$$

where E_a is the activation energy, R, is the universal gas constant (8.314 J•mol^{-1}•K^{-1}), and T is the temperature in Kelvin.

$$(3) \quad t_{1/2} = 0.693/k$$

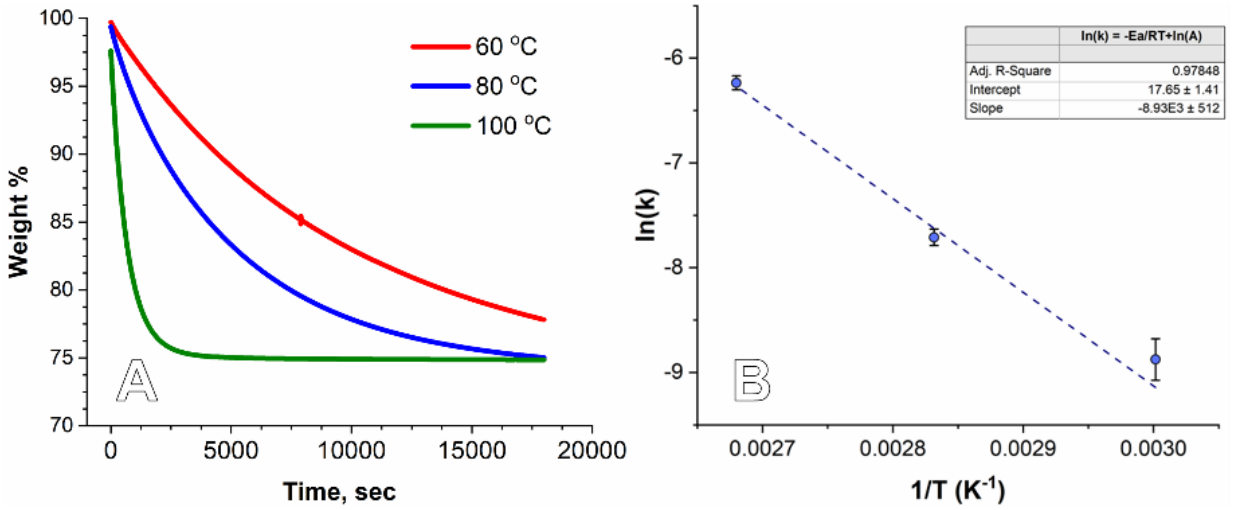

Figure 7. (*A*) Isothermal release profiles at 60, 80, and 100 °C for nanofibers made from a solution of 18.0 wt% nylon and 50 rel. wt% DEET. (*B*) Determination of the activation energy of the release of DEET using the Arrhenius equation (eq.2). Error bars are the result of triplicate analysis for each temperature.

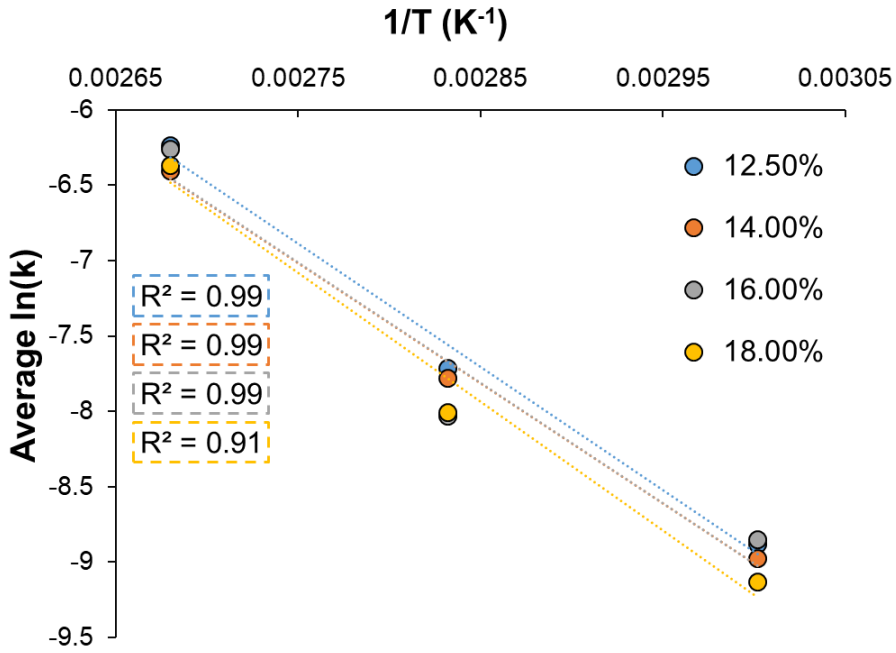

Figure 8. Linear fits for the Arrhenius analysis used to determine the activation energy of electrospun nanofibers fabricated from samples made with 12.5, 14.0, 16.0 and 18.0 wt% nylon and 50 rel. wt% DEET.

The release profiles for 18 wt% nylon and 50 rel. wt% DEET at 60, 80 and 100 °C are shown in Figure 7A. As expected, the loss of DEET becomes more rapid at elevated temperatures as the rate of evaporation increases. The rate constant from the first-order fit of the release profile at each temperature was used to determine the activation energy as shown in Figure 7B. The linear fit for the temperature-dependence of the natural log of the rate constant used to determine the activation energy is shown in Figure 8 for 12.5, 14.0, 16.0 and 18.0 wt% nylon with 50 rel. wt% DEET. The activation energy, rate constant, and half-life for the release of DEET at 20 °C for samples made with 50 rel. wt% DEET and varying concentrations of nylon is given in Table 3.

Table 3. Activation energy, rate constant, and half-life of DEET at 20 °C from electrospun fibers fabricated with varying concentrations of nylon.

[Nylon], wt%[a]	E_a (kJ/mol)	k (s^{-1}), at 20°C	$t_{1/2}$(hours), at 20°C
12.5%	74.2 ± 4.3	$2.76x10^{-6} \pm 1.10x10^{-6}$	69.7 ± 19.9
14.0%	64.6 ± 5.1	$4.63x10^{-6} \pm 1.89x10^{-6}$	41.6 ± 12.1
16.0%	67.6 ± 2.4	$4.96x10^{-6} \pm 1.03x10^{-6}$	38.8 ± 6.69
18.0%	71.6 ± 6.8	$3.07x10^{-6} \pm 1.93x10^{-6}$	62.7 ± 24.2

[A] Samples made with 50 wt% DEET relative to nylon. Error bars are calculated using the error in the slope of the linear fit of the Arrhenius analysis resulting from triplicate measurements

The nylon concentration did not have a significant effect on the activation energy of DEET loss with all samples falling between within experimental error. Similarly, the rate constant for the loss of DEET at 20 °C varied between $2.8x10^{-6}$ – $5.0x10^{-6}$ s^{-1} and did not significantly vary with respect to the nylon concentration. Importantly, although there are significant differences in fiber morphology between samples made with 12.5 – 18.0 wt% nylon, the morphological differences do not significantly affect the release profile and all samples show extended release lifetimes with half-lives greater than ca. 40 h. The lack of correlation between fiber morphology and release rate suggests that the dominant factor in repellent release is strong interaction between DEET and nylon.

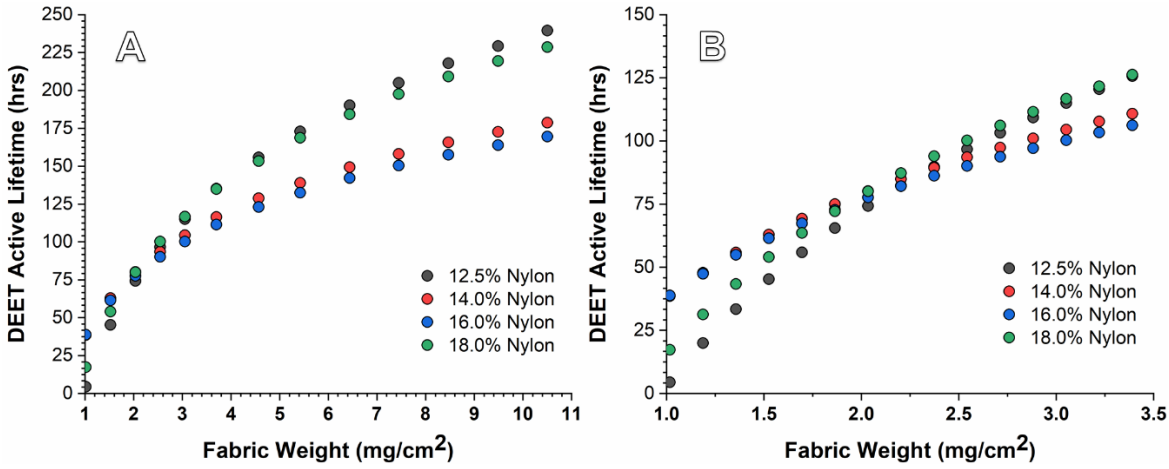

Figure 9. The active lifetime of fibrous mats fabricated with 12.5, 14.0, 16.0 and 18.0% nylon and 50 rel. wt% DEET with respect to the weight (mg•cm^2) of material. The active lifetime is defined as the amount of time necessary for the release rate to drop below the minimum value of 2.6 µg•cm^{-2}•hr^{-1}.[23] The lifetimes are estimated for a range of fabric weights ranging from lightweight (*A*) to ultra-lightweight materials (*B*).

To estimate the duration of repellent activity of the materials, the effective lifetime was determined with respect to the weight of the fibrous mat. It has been reported that the minimum rate of DEET evaporation necessary to repel mosquitoes is 2.6 µg•cm^{-2}•hr^{-1}.[23] Using the minimum rate of DEET evaporation, the percent of DEET present within the fibers given in Table 2 (recorded as the mass loss), and the rate constant that describes DEET release at 20 °C (Table 3), the active lifetime of electrospun fibrous mats was determined over a range of possible weights (Figure 9).

Lightweight fabrics, such as viscose and cotton, are generally considered to be those that weigh less than 14 mg•cm^2. The lifetime of electrospun mats was estimated for lightweight (Figure 9A), and ultra-lightweight samples (Figure 9B). All samples demonstrated long active lifetimes for DEET with the active lifetimes ranging from ten to hundreds of hours depending on the composition and the weight of the sample. For example, a sample weighing 2 mg•cm^2, which is similar in weight to breathable athletic attire, is estimated to provide ca. 75 h of protection. There are differences in the release profiles with respect to the concentration of nylon for lightweight and ultra-lightweight materials. For samples weighing less than 2 mg•cm^2, due to there being less

repellent present on aggregate, the effective lifetime is dominated by the rate constant as illustrated by the longer active lifetimes for samples made at 14.0 and 16.0 wt% nylon when compared with those made at 12.5 and 18.0 wt%. At higher sample weights, however, the effective lifetime is dominated by the amount of sample, and thus the amount of DEET present, and although all samples showed similar DEET loading, samples made at 12.5 and 18.0 wt% have longer active lifetimes when compared with those for 14.0 and 16.0 wt% nylon because of their longer half-life and subsequently lower rate constant. Almost regardless of the fabric weight, however, this system significantly outperforms topical application by orders of magnitude. Defining the maximum effective lifetime for the electrospun nanofibers by evaluating their release profiles helps to define the optimal parameters to transition this work to functional fabrics and textiles.

4.5. DEET release mechanism.

It can be assumed that DEET is universally dispersed within the polymer matrix which may result in uniform evolution of DEET from the material, however, there may be differences in the evaporation rates with respect to the distribution of the repellent within the nanofiber (i.e. closer or father from the fiber surface). In order to accurately define release profiles, it is necessary to know the mechanisms involved to accurately predict the kinetics of repellent release. Many current systems are based on well-known drug delivery systems and have since been adapted to repellent release. There are many kinetic models used to accurately quantify the release rate of repellent; the most popular of which are the Higuchi, Korsmeyer-Peppas, and Mapossa models, however, these models are based on empirical observations and therefore are less suitable when the release mechanism is unexplored.[7] In such cases, the Weibull distribution, as described by Avrami's equation (eq. 4) and it's linearized form (eq. 5), can be used to correlate diffusion in complex

systems.[35-37]

$$(4) \quad y = e^{-(kt)^n}$$

$$(5) \quad \ln(-\ln(y)) = n * \ln(k) + n * \ln(t)$$

where *y* is the fraction released, *k* is the rate constant, *t* is time, and *n* (the slope of eq. 2) is a parameter representing the release mechanism.

Originally used to express the kinetics of crystal growth of polymers, Avrami's equation has become a popular tool to understand the release mechanism in novel systems and has been previously used to predict the release of core material. When the linearized form is used (eq. 2) the slope of the resulting linear fit is described by *n* and can be used to describe diffusion processes. If $n \approx 1$, the release can be explained by a 1st order mechanism, if $0.75 < n < 1$, the results correspond to Fickian diffusion, and if $n > 1$, the release mechanism is complex and rapid.

Using the isothermal release profiles described earlier, the value of the shape parameter was determined for electrospun nylon fibers fabricated from 12.5, 14.0, 16.0, and 18.0 wt% nylon, each with 50 rel. wt% DEET, at 60, 80 and 100 °C to characterize the change in release profile with temperature. Figure 5 shows the release profiles for 18.0 wt% nylon with 50 rel. wt% DEET and the linear fit using eq. 2. The calculated values of *n* for all concentrations of nylons tested can be found in Table 4.

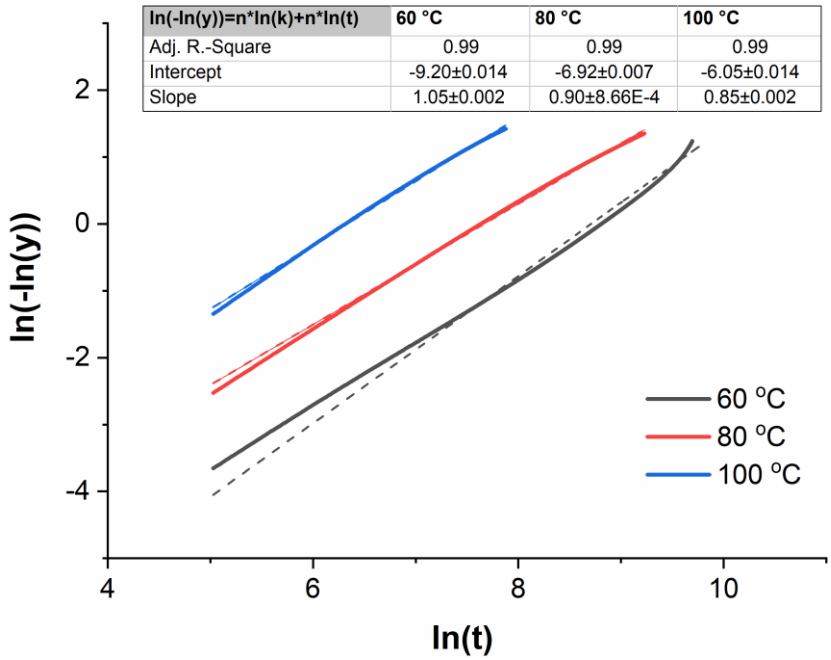

Figure 10. A plot of the release profile for electrospun fibers from a solution containing 18.0 wt% nylon with 50 rel. wt% DEET to determine the shape parameter, *n*, as the slope of the linear fit according to equation 5. The release profiles were obtained from isothermal experiments at 60, 80 and 100 °C (solid line). The data from the linear fit (dashed line) to the data is given in the inset table.

Table 4. Average Values of ***n*** calculated from fitting to the Avrami Equation.

[Nylon], wt % with 50 wt% DEET	***n*** (60 °C)	***n*** (80 °C)	***n*** (100 °C)
12.5	1.06±0.04	0.91±0.03	0.87±0.07
14.0	0.90±0.18	0.89±0.03	0.82±0.01
16.0	0.91±0.01	0.91±0.06	0.76±0.06
18.0	1.11±0.02	0.90±0.05	0.81±0.22

n is the slope from the fit according to the Avrami equation. Error bars based on triplicate measurements.

For all concentrations of nylon tested, $n > 0.75$ suggesting the data can be modeled using a 1st order equation. As the temperature increases, however, there is a noticeable decrease in the shape parameter suggesting that, at high temperatures, the release starts to become more consistent

with Fickian diffusion. At high temperatures, the energetic advantage of the DEET/nylon interaction is overcome leading to concentration dependent diffusion dominated release. Likewise, at low temperatures (< 60°C) the release mechanism is dominated by the molecular interactions between DEET and nylon and thus cannot be described by a traditional vapor diffusion mechanism, which relies on the vapor pressure and the surface area of the material to determine the release rate.

Interestingly, the shape parameter for samples made at 12.5 and 18.0 % nylon are similar, and shape parameter for samples made at 14.0 and 16.0% nylon are similar. This is further correlated with the release rates shown previously in Table 3 with both 12.5 and 18.0 % nylon displaying the longest half-lives and slowest release rate constants. However, there is a lack of strong correlation between fiber morphology and release profile as the samples made with 12.5 and 18.0 wt% nylon display significant differences in fiber morphology.

4.6. Mechanical Analysis of DEET Fibers

The effect of nylon concentration in the electrospinning solution and the presence of 50 rel. wt% DEET on the mechanical properties of electrospun mats were evaluated (Figure 11). The mechanical properties of electrospun mats were tested using and Instron 345C-1 equipped with a 50 N load cell and pneumatic grips. Electrospun mats were collected for 150 minutes before being cut into 1 x 5 cm strips to be tested.

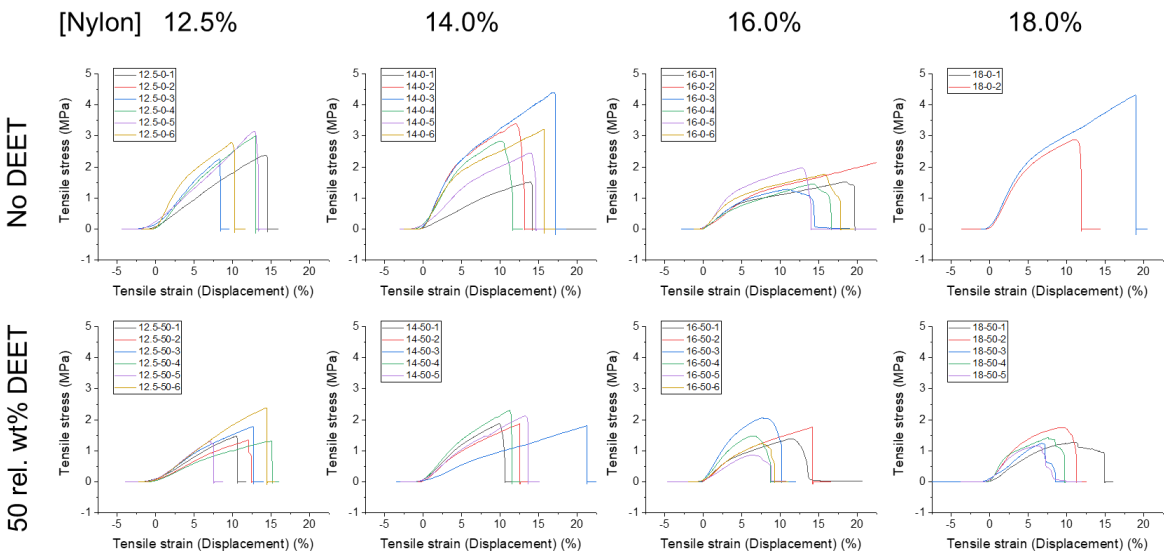

Figure 11. Stress-strain curves of electrospun nonwoven mats prepared from various nylon concentrations without DEET (top row) and nylon fibers loaded with 50 rel. wt% DEET (bottom row).

The electrospun fibrous mats were evaluated for stress at break, strain at break, and Young's modulus (Figure 12). Nylon concentration had minimal effect on tensile strength, extensibility, and modulus. Incorporation of DEET at 50 rel. wt% decreased the tensile strength in the 12.5 and 14.0 wt% nylon fibers, however significant strength was maintained considering the high repellent loading. The incorporation of DEET had little effect on the extensibility and Young's modulus of the electrospun mats. Previous studies have shown that the incorporation of > 50 rel. wt% DEET within poly-lactic acid nanofibers lead to the formation of voids within the polymer nanofibers.[38] The mechanical properties of the nonwoven mats, along with the SEM images (Figure 6) of electrospun fibers, indicate there was no significant loss of polymeric integrity for fibers with different morphologies, or with the incorporation of DEET.

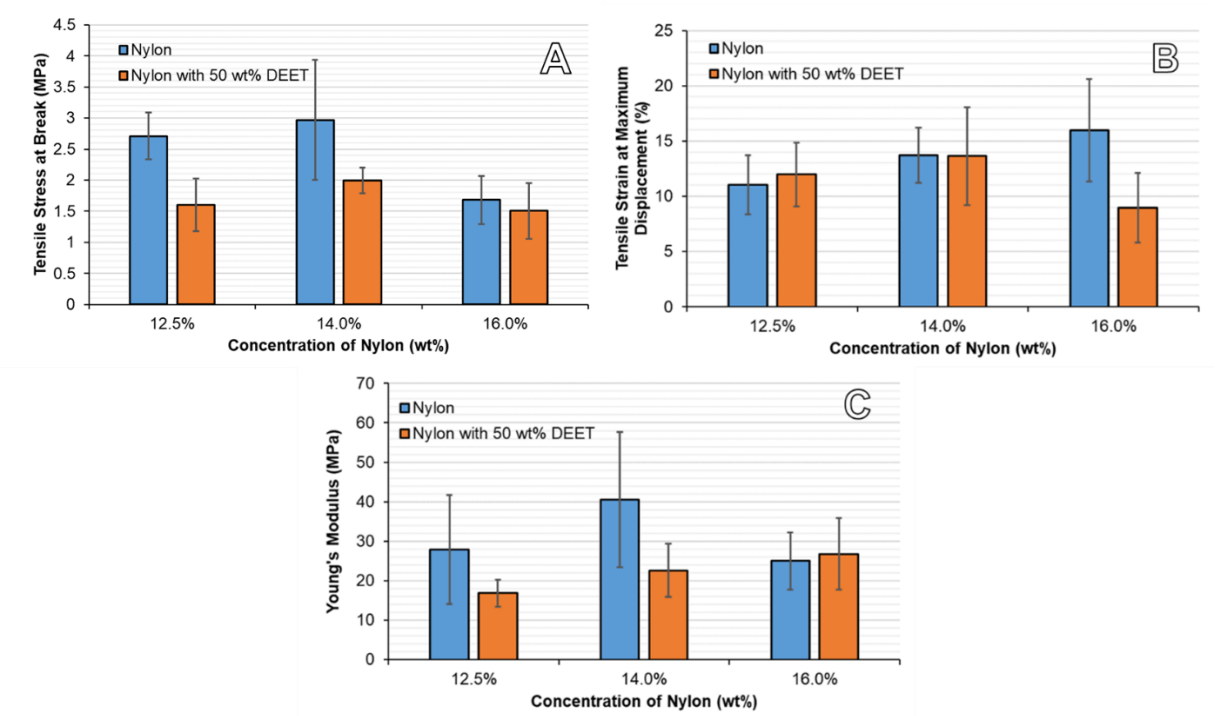

Figure 12. Mechanical properties of electrospun nylon fibers. Nylon fibers were fabricated from solutions containing 12.5, 14.0 and 16.0 wt% nylon in formic acid. For Nylon/DEET fibers, solutions were prepared at the noted concentration of nylon with added 50 rel. wt% DEET.

The tensile stress at break (Figure 12A) is a measure of the tensile strength of the materials. Surprisingly, despite the nonwoven form of the nylon mats, the electrospun mats exhibited tensile strength (tensile stress at break) in the range of 1.5-3.0 MPa, which is comparable to LDPE films, Variability in the stress-strain replicates was attributed to the fibrous, nonwoven nature of the mats. Encouragingly, the fibers maintained significant tensile strength even with the incorporation of 50 rel. wt% of DEET. The strain at maximum displacement (Figure 12B) is a measure of the maximum elongation, or extensibility, of the material before breaking. The electrospun mats were able to elongate ca. 10% independent of the concentration of nylon or the presence of DEET. Finally, the Young's modulus (Figure 12C) is calculated from the initial slop of the stress-strain curve, and indicates the relative effort required to stretch the nonwoven mats. The Young's moduli was expectedly relatively low, due to the thin, nonwoven nature of the mats. Furthermore, the

moduli were unaffected by both nylon concentration and DEET incorporation for all samples evaluated. Overall, the mechanical properties of nylon mats were largely maintained upon incorporation of DEET up to 50 rel. wt%. Therefore, engineering considerations are relatively minimal for DEET loading with respect to mechanical properties for potential future material fabrication.

4.7. DEET Fibers: Conclusions

Encapsulation of repellents is a promising strategy to both limit direct skin contact in addition to controlling evaporation rates and extending the lifetime of repellency. Electrospun nylon fibers with incorporated DEET were fabricated and are shown to retain ca. 80% of the initial amount of repellent. Incorporation of up to 50 rel. wt% DEET has no detrimental effect on fiber morphology, but increasing the concentration of nylon in the polymer solution leads to the formation of electrospun ribbons at high concentrations. The change in fiber morphology, however, had little effect on the retention of DEET in the fibrous mats, or their thermal stability. The rate constant of DEET evaporation at room temperature was calculated using a series of isothermal TGA experiments and from the rate constant, the effective lifetime of the fibrous mats was estimated. It was shown that the effective lifetime was dependent on the amount of sample (i.e. the weight) and the concentration of nylon. For samples akin to ultra-lightweight fabric, it was estimated that DEET repellency would be active for > 72 h, which far outperforms common topical application. For heavier samples, the active lifetime was even greater with estimations of ca. 200 h. The release was consistent with a first-order mechanism further suggesting that the evaporation of DEET is controlled by strong interactions with the nylon polymer matrix. Nylon is a common commercial fabric and these results open the possibility of incorporation of repellents into fabrics

and textiles for clothing with active, long-lasting repellency. Future work will involve the determination of the extent to which the fiber morphology affects the mechanical properties of the electrospun fibers to determine which is best suited for transition into woven textiles along with laundering and durability tests.

5. Results and Discussion: Task 1 - Permethrin Fibers

Permethrin is a synthetic contact insecticide originally derived from crushed chrysanthemum flowers. It is a powerful contact killer that shows activity against mosquitoes, fleas, ticks and more.[39] Permethrin is commonly used by the military in spray form to treat uniforms for extended protection. It has been shown to exhibit extended protection relative to DEET, but unlike DEET, it cannot be applied directly to the skin. Generally applied as a treatment to textiles, permethrin can remain active for weeks after multiple laundering sessions.[40] In this section, the effects of encapsulation of permethrin within electrospun nylon nanofibers of fiber morphology, permethrin loading, and thermal behavior are discussed.

5.1. Permethrin fiber morphology

Nylon fibers were electrospun from solutions containing 12.5 wt% nylon 6,6 in formic acid and 0.5 – 10 rel. wt% permethrin relative to nylon. Since permethrin is a solid at room temperature, its dissolution into polymer solution and subsequent encapsulation into electrospun fibers is non-trivial. At all concentrations of permethrin evaluated, uniform, defect-free nanofibers were observed. Microscope images of electrospun fibers with 10 rel. wt% permethrin are shown in Figure 13. Although the toxicity of permethrin is dependent on direct contact with an arthropod, previous studies have shown that encapsulation within a polymeric network does not interfere with its efficacy.[40] Importantly, the structural integrity of the electrospun nanofibers in this study are unaffected by the presence of up to 10 rel. wt% permethrin.

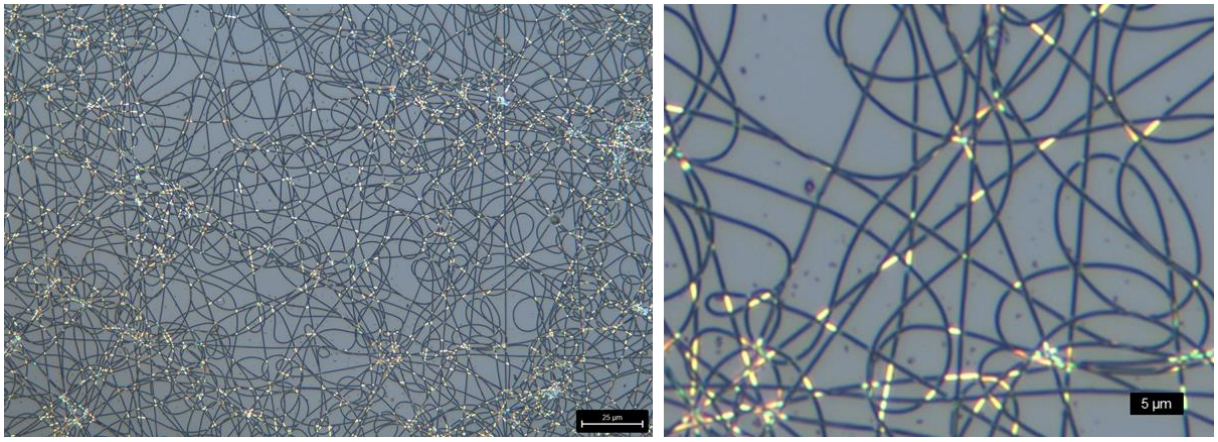

Figure 13. Optical microscope images of electrospun nylon fibers loaded with 10 rel. wt% permethrin.

5.2. Permethrin thermal release profile

The thermal behavior of permethrin-doped nylon fibers was characterized using TGA to identify loading concentration of permethrin in the electrospun fibers, as well as to identify potential thermal release of permethrin. Nylon fibers were heated at a rate of 10 °C/min to 600 °C. The mass loss at ca. 120 °C was attributed to the loss of permethrin. With increasing concentrations permethrin, there is a corresponding increase in the mass loss at 120 °C. In nylon fibers loaded with permethrin at 10 rel. wt% (Figure 14, pink trace), a mass loss of 7.7% occurred at 120 °C which corresponds to an 85% retention of permethrin in the final electrospun fibers from the initial electrospinning solution. Furthermore, the nylon-permethrin fibers are stable at temperatures up to ca. 400 °C, at which temperature the nylon undergoes thermal degradation. Permethrin loading affected the degradation onset temperature of the nylon mats, the reason for which is subject of current investigations. Due to the fact that permethrin is a contact-killer, the previously described methods of determining the release rate using isothermal TGA do not apply. Future work will involve measuring the efficacy of the as-spun, as well as laundered, nylon-permethrin electrospun fibers against live insects.

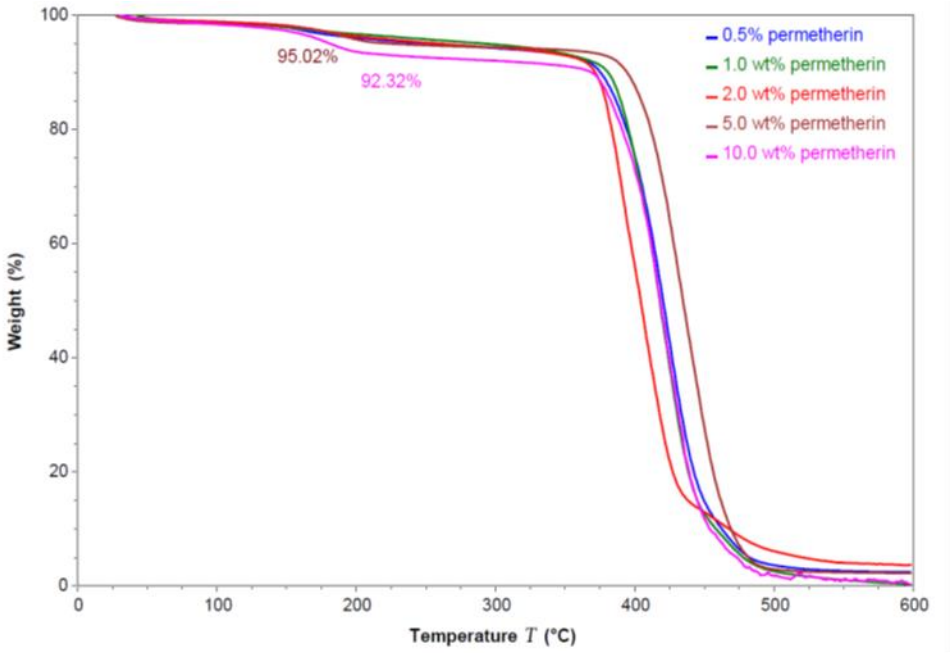

Figure 14. TGA ramps demonstrating loading capacity of permethrin-loaded nylon fibers.

This preliminary evaluation demonstrates the potential to incorporate permethrin into electrospun nylon fibers at relatively high loading concentrations. This approach demonstrates the feasibility of direct incorporation of solid insecticide into a solution-based electrospun fiber, for which the potential applications are broad. A fibrous material that is pre-loaded with permethrin eliminates the need for the end-user to apply permethrin themselves, which can be a time consuming and potential hazardous process, and would provide immediate efficacy against arthropods.

6. Results and Discussion: Task 1 - DEET and Picaridin Mixed Repellent Fibers

6.1. Mixed Repellent Fiber Loading and Morphology

Previous studies have shown that mixed-repellent systems have potential to impart synergistic effects on repellency that increases the lifetime, and efficacy, of the repellent. For example, an increase in effectiveness was observed when cinnamon oils were blended with geranium and rosemary oils resulting in a significant increase in repellent lifetime and a decrease in the required dosage for a repellent response.[41] Inspired by those observations, we examined a system of DEET/Picaridin in various ratios to identify potential synergistic effects on the repellent lifetime. To fabricate the mixed-repellent fibers, 12.5% nylon was dissolved in formic acid and 50 rel. wt% total repellent (DEET + Picaridin) was added. The DEET/Picaridin system was examined at relative mass ratios of 100/0, 70/25, 50/50, 25/75, and 0/100. The solutions were electrospun at a rate of 0.9 mL•hr^{-1}, a distance of 12 cm, and an applied voltage of 15 kV.

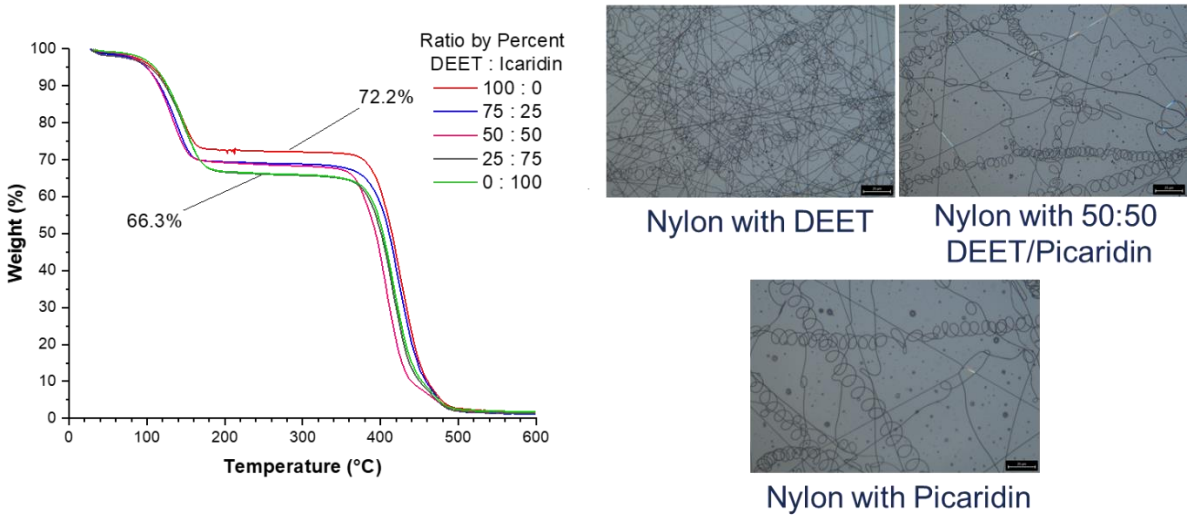

Figure 15. TGA (left) and optical microscopy (right) of mixed repellent fibrous mats.

Optical microscopy was used to evaluate the effects of mixed repellent loading on electrospun nylon fiber morphology (Figure 15, right). There are no noticeable differences in the fiber morphology for mixed repellent systems when compared to those fabricated with pure DEET, or Picaridin. Fibers remained uniform and cylindrical with no significant changes in diameter. TGA was employed to determined the repellent concentration in the fibers by measuring the mass loss at ca. 200 °C (Figure 15, left). As the concentration of Picaridin is increased, there is a corresponding increase in the retention of repellent within the electrospun nanofibers. At the highest concentration of Picaridin, 98% of the repellent was retained compared with 84% for pure DEET fibers. The mixed-repellent systems all have ca. 94% retention of repellent. The difference in retention between DEET and Picaridin was attributed to the relative volatility of the two repellents. The vapor pressure of DEET (2.0×10^{-3} mmHg) is greater than that of Picaridin (4.4×10^{-4} mmHg).[42-43] Therefore, during the electrospinning process, DEET exhibits more evaporation resulting in a lower percentage of the DEET retained in the polymer fibers than Picaridin.

6.2. Mixed Repellent Release and Kinetics

The release rate of the mixed-repellent fibers was characterized using isothermal TGA as previously described in Section 0, thermal analysis. Example isotherms and first-order reaction model fits to the data are shown in Figure 16.

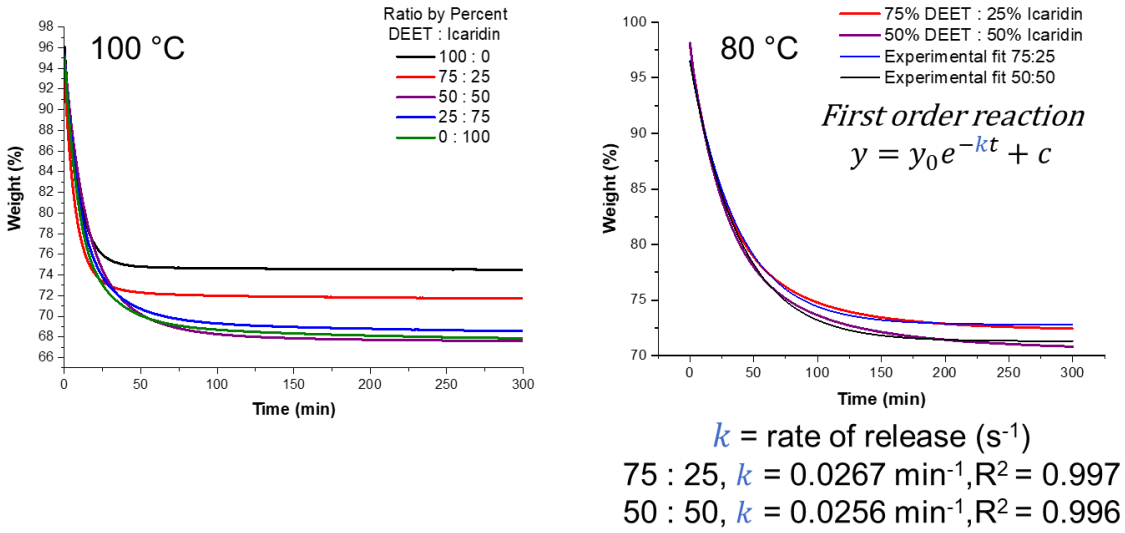

Figure 16. Isothermal TGA of dual repellent fibers at 100 °C (left) and 80 °C (right), with calculated 1st order kinetic parameters (bottom right).

As expected, all mixed repellent fiber samples exhibited faster release of repellent at higher temperatures. At 100 °C, the equilibrium baseline shifted to higher weight percentages (less mass loss) with decreasing ratio of DEET/Picaridin due to the greater relative retention of picaridin in the electrospun fibers. At all temperatures, the repellent loss curves were fit to a first-order decay equation with excellent agreement ($R^2 > 0.99$), indicating the capability to model and predict the amount of repellent release at time points beyond those measured. Figure 16A *right* shows example isotherms at 80 °C for DEET/Picaridin ratios of 75/25 and 50/50 fit to a first-order model using Eq. 1. The fact the the mixed repellent systems fit well to a 1st order loss model suggests that the release of each repellent was mutually independent of one another in the mixed systems and that there was minimal chemical interaction between the two.

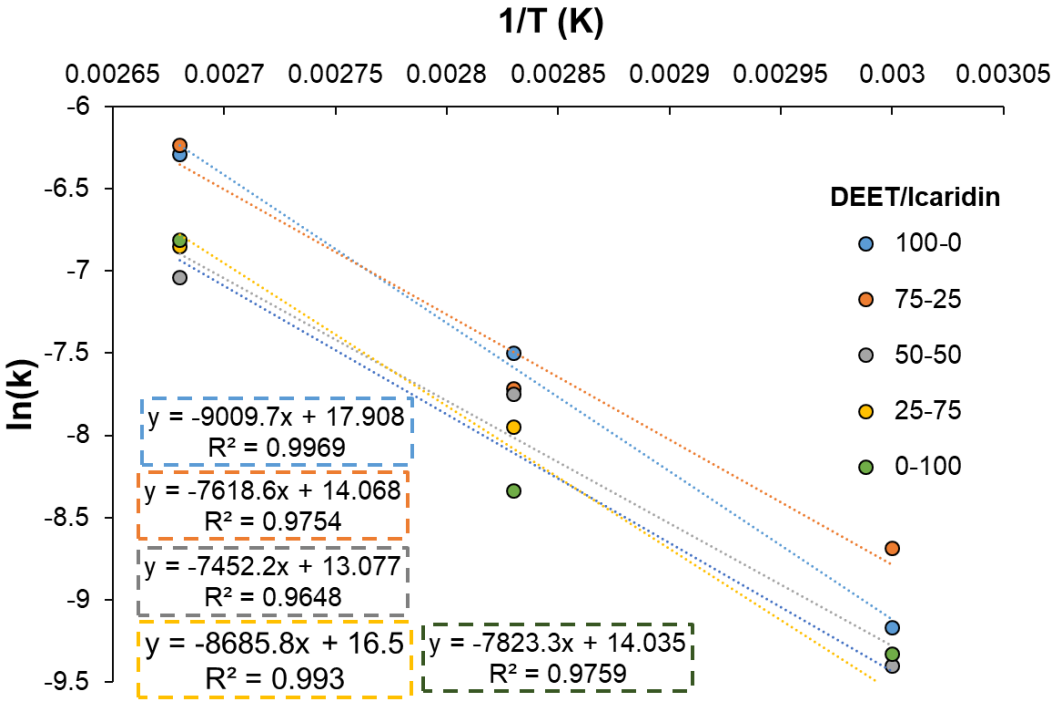

Figure 17. Arrhenius plot to determine activation energy as a function of picaridin loading relative to DEET content.

The activation energy and half-life were calculated using equations 2 and 3 using the rate constants calculated from a first-order fit of the decay profiles at the three different temperatures. The linear fit according to Eq. 2 is shown in Figure 17. The activation energy, rate constant, and half-life for mixed repellent systems are summarized in Table 5.

Table 5. Insect Repellent Release Kinetics

Ratio of DEET/Icaridin*	Ea (kJ/mol)	k (s^{-1})	$t_{1/2}$ (hours at 20 °C)
100:0	74.9	2.68×10^{-6}	71.6
75:25	63.3	9.00×10^{-7}	214
50:50	61.9	4.35×10^{-6}	44.2
25:75	72.2	1.98×10^{-6}	96.9
0:100	65.0	3.20×10^{-6}	60.1

*Samples made from a solution of 12.5 wt% nylon with 50 wt% repellent relative to nylon.

The activation energy of repellent evaporation for nanofibers with pure DEET was consistent with previous results shown in Table 3. Surprisingly, nanofibers fabricated with pure Picaridin had a moderately lower activation energy than those with pure DEET and displayed a shorter half-life by ca. 10 hours. In neat repellent systems, it has been observed that Picaridin-based repellents are longer-lasting than those that are DEET-based.[44] The shorter half-life of the Picaridin/nylon fibers than the DEET/Picaridin fibers suggests that the interaction between Picaridin and nylon is not as strong as that of DEET and nylon. Encouragingly, two of the mixed-repellent systems evaluated displayed significantly longer half-lives than the neat repellent fibers. The half-life of fibers made with a DEET/Picaridin at a ratio of 25/75 increased by 25.4 and 36.8 hours relative to DEET and Picaridin fibers, respectively. Furthermore, fibers made with a ratio of 75/25 had a half-live >3x longer than neat repellent fibers suggesting that there may be a significant synergistic effect that that slows repellent evaporation and results in a significant increase in half-life. A 50/50 mixture of repellents had a lower half-life relative to neat repellent fibers suggesting that there may be incompatibilities between the pure repellents in solution and in the polymer matrix. In addition to potential physical synergistic effects, there is potential that dual release insect repellents may improve repellency through biological means by providing multiple mechanisms of repellency (e.g. odor masking and olfactory obstruction). As such, continuing efforts will focus on evaluating the synergistic effect further by evaluating the efficacy of these materials against live mosquitos.

7. Results and Discussion: Task 2 - Preliminary Electrospun Yarns

Although electrospun mats are ideal coatings for surfaces and screens, electrospinning is more difficult to scale than traditional filaments and fiber for conventional textile applications. One promising approach to alleviate scaling issues and to improve mechanical properties is to convert electrospun filaments into electrospun yarns via mechanical twisting.[45] Therefore, preliminary electrospun yarns were produced from the insect repellent-loaded nylon electrospun fibers to evaluate their morphology and determine feasibility of fabrication (Figure 18). In Section 4.6, it was shown that the mechanical strength and stability of the electrospun nylon fibers were maintained with the incorporation of up to 50 rel. wt% DEET relative nylon.

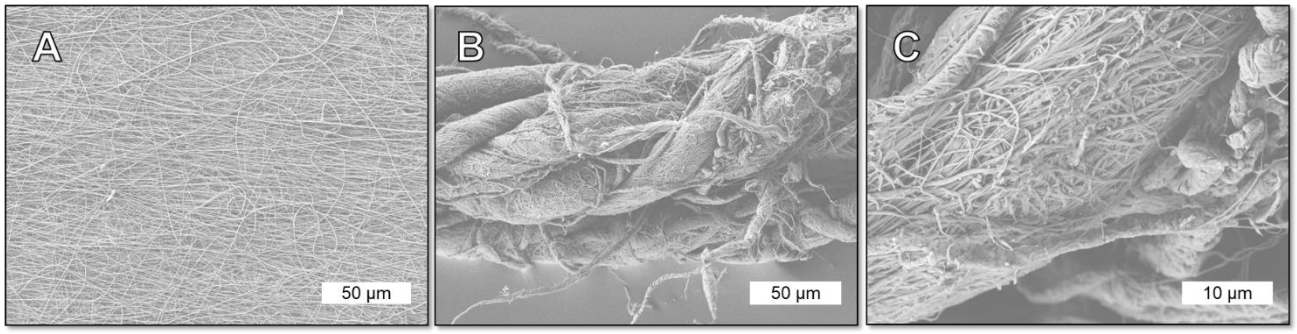

Figure 18. SEM images of a yarn of electrospun nylon fabricated from a solution containing 12.5 wt% nylon and 50 rel. wt% DEET spun onto a rotating drum collector at 1000 rpm for 1 hour. (A) An SEM image of the electrospun tow before twisting into a yarn showing approximate orientation of the nanofibers in the horizontal direction. (B) An SEM image of the manually twisted yarn. (C) An SEM image showing the nanofiber composition of the yarn.

First, a solution containing 12.5% nylon in formic acid with 50 rel. wt% DEET was electrospun onto a rotating drum collector moving clockwise at 1000 rpm. The solution was dispensed at a flow rate of 0.9 $mL \bullet hr^{-1}$ at a distance of 12 – 15 cm and an applied voltage of 15 kV. Spinning onto the rotating drum lead to the formation of an ordered tow of electrospun nanofibers that was then manually twisted into a yarn (Figure 18). An SEM image of the yarn

clearly shows the individual nanofibers were retained and incorporated into individual filaments there were twisted together to form the yarn (Figure 18C). Significantly, the yarn was ca. 150 µm in diameter, which is comparable to commercially available polymer filaments used in conventional fabric manufacturing. Furthermore, the nanofibers maintained their morphology throughout the twisting process. Since the electrospun fiber morphology is maintained when twisted into a yarn, it is expected that the yarn should exhibit similar repellent release profiles as the non-woven mats. However, some differences in release could result due to different diffusion rates from fibers and filaments buried in the center of the yarn than those on the outside. Future work will involve characterizing the release rate of repellent from electrospun yarns, subjecting the yarns to multiple simulated laundering cycles, evaluating the mechanical properties of the yarns, and evaluating retention of repellent. The electrospun insect repellent nylon fibers proved compatible with mechanical yarn fabrication techniques.

8. Summary and Conclusions

8.1. Summary

We have demonstrated the feasibility of electrospinning a rapid prototyping method to fabricate and made substantial progress in the development of novel composite fiber designs for sustained insect repellent release. Fibers with monofilament structures containing mixed components of different classes of insect repellents were fabricated. We successfully incorporated three (3) different repellents into electrospun fibers individually, including Picaridin (up to 50 rel. wt%), DEET (up to 50 rel. wt%), Permethrin (0.2-10 rel. wt%). Additionally, dual-insect repellent composites containing Picaridin and DEET were designed, fabricated, and evaluated. The electrospun nylon fibers were also successfully twisted into yarns, thus demonstrating a potential direct transition pathway. Sustained release of insect repellent was achieved and we identified key parameters to transition to live insect testing, which is currently underway.

We achieved significant retention of DEET (>80%) in composite electrospun fibers. Incorporation of up to 50 rel. wt% DEET relative to nylon has no detrimental effect on fiber morphology. The effective lifetime of DEET fibers was dependent on the amount of sample (i.e. the weight) and the concentration of nylon. For samples comparable to ultra-lightweight fabric, it was estimated that DEET repellency would be active for > 72 h, which far outperforms common topical application. For heavier samples, the active lifetime was even greater with estimations ca. 200 hours. The release was consistent with a first-order mechanism further suggesting that the evaporation of DEET is limited by strong interactions with the polymer matrix.

Electrospinning successfully enabled the rapid fabrication and evaluation of mixed repellent fibers. Specifically, DEET and picaridin (total 50wt%) were both incorporated into fiber composites at various ratios and exhibited synergistic behavior resulting in an extended release

rate with half-lives up to 90 h. This has potential to result in improved repellency against live insect by a combination of improved release kinetics and multiple repellent mechanisms.

We further demonstrated the capability of electrospinning as a facile fabrication technique with the incorporation of Permethrin at concentrations up to 10 rel. wt%. It should be noted that the incorporation of permethrin was non-trivial because it is a solid at room temperature. The solid permethrin was dissolved directly into the nylon-formic acid electrospinning solution prior to electrospinning, which proved to be an effective method to incorporate and retain most of the permethrin into nylon microfibers. The permethrin-fibers exhibited significant thermal stability and will be subject of forthcoming live insect testing. The successful incorporation of permethrin insecticide, in addition to the picaridin and DEET volatile repellents, widens the range of potential composite fiber designs for continued development.

Electrospun yarns were successfully manufactured from electrospun insect repellent composite fibers through a mechanical twisting method. The electrospun nylon fibers demonstrated sufficient mechanical integrity to withstand the yarn twisting process. Fiber morphology was maintained and minimal fracture occurred. This result represents an important first step that demonstrates the capability to manufacture electrospun yarns from the various electrospun composite fibers evaluated to date. Electrospun yarns have potential to be used in more conventional textile manufacturing techniques since the yarn diameter is comparable to traditional filaments and fibers.

8.2. Significance and Implications

Nylon is a common commercial fabric and these results open the possibility of incorporation of repellents into fabrics and textiles for clothing with active, long lasting repellency.

Electrospinning was able to overcome potential challenges with the retention of volatile repellents (DEET) through material processing. To date, we have developed a library of fiber designs with multiple insect repellents and/or insecticides combinations and loadings for potential transition to the next-phase of development, fiber extrusion. We identified high insect repellent loading bounds and measured the effects of loading and polymer concentration on release kinetics. These data will be will be used to inform the engineering design and fabrication of composite fibers through manufacturing techniques with greater potential for scale-up.

The electrospun insect repellent fibers have potential to deliver impact as a standalone material in the form of a non-woven cloth for long-lasting, localized insect repellency in high contact areas, such as collars, cuffs, hats, or patches. Such applications would afford several benefits over current spray applications including no spraying required, no oily residue, easy application, and importantly long-lasting repellency (>70 h), all while being a light and flexible fabric.

8.3. Next Steps

The results to date clearly prove electrospinning as an effective rapid prototyping method to fabricate novel composite nylon fibers. Future work will involve determining the extent to which the fiber morphology affects the mechanical properties, laundering, and durability of the electrospun fibers to identify which are best suited for transition into extruded fibers. Additionally, electrospinning will be employed to prototype other textile-relevant polymers to assess their potential for insect repellent composites to broaden the range of applications and enable transition paths. Live insect testing is currently underway and will be critical to identify and select fiber designs for evaluation with fiber extrusion methods. Electrospun fiber formulations will be down-

selected and adapted for compatibility with fiber extrusion methods. The performance of extruded composite fibers, including insect repellent retention, efficacy against live insects, and durability (mechanical, thermal, and washing), will be evaluated to identify designs compatible for scale-up. The progress reported here represents a strong foundation upon which to continue to develop and deliver long-lasting insect repellent fibers for textile applications.

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