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BASIC SCIENCE REVIEW

The March Against Onychomycosis: A Systematic Review of the Sanitization Methods for Shoes, Socks, and Textiles

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Drug based treatment of superficial fungal infections, such as onychomycosis, is not the only defense. Sanitization of footwear such as shoes, socks/stockings, and other textiles is integral to the prevention of recurrence, and reduction of spread for superficial fungal mycoses. The goal of this review was to examine the available methods of sanitization for footwear and textiles against superficial fungal infections. A systematic literature search of various sanitization devices and methods that could be applied to footwear and textiles using PubMed, Scopus, and MEDLINE was performed. Fifty-four studies were found relevant to the different methodologies, devices, and techniques of sanitization as it pertains to superficial fungal infections of the feet. These included topics of basic sanitization, antifungal and antimicrobial

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materials, sanitization chemicals and powder, laundering, ultraviolet, ozone, non-thermal plasma, microwave radiation, essential oils, and natural plant extracts. In management of onychomycosis it is necessary to think beyond treatment of the nail, as infections enter through the skin. Those prone to onychomycosis should examine their environment, including surfaces, shoes, and socks, and ensure that proper sanitization is implemented.

Superficial mycoses are one of the most common infections across the globe ^{1,2}. The feet provide an optimal environment for fungal growth; warm, moist (due to sweat), and often enclosed by shoes and socks. As such, superficial fungal infections affecting the feet or nails are prevalent. There are a number of available treatment methods for onychomycosis, with topical (e.g., efinaconazole, tavaborole, ciclopirox), oral (e.g., terbinafine, itraconazole, fluconazole), or a combination of both, being the most popular ². However, treatment of onychomycosis alone should not be the sole line of defense. Sanitization of shoes, socks/stockings, and other textiles (as well as the feet themselves through proper hygiene) is integral to the reduction of spread and recurrence of superficial fungal infections ³.

The goal of the present review was to examine the currently available methods of sanitization for footwear and textiles against superficial fungal infections, and assessing which are effective or not.

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Materials and Methods

A protocol for this study was registered with the international platform of registered systematic review and meta-analysis protocols (INPLASY, protocol ID: 2021110070), following guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)⁴. A literature search of various sanitization devices and methods that could be applied to footwear and textiles using PubMed, Scopus, and MEDLINE was performed. Only primary research articles which were written in English were retained, and the only date restriction was the date the searches were executed (November 10, 2021). To increase the comprehensiveness of this review, bibliographies of prominent review articles on this topic were manually searched^{2,5-14}. For both search methods, the selection of articles for inclusion was independently performed by two authors: D.C.H and A.J.S. Disagreements were resolved with the third author (A.K.G).

Results

The systematic search results are illustrated in Figure 1. The initial search yielded a total of 127 studies. A total of 46 studies were removed before screening due to reasons such as duplications and being published in languages other than English. After screening article titles, 81 articles were considered for screening of abstracts. After a complementary bibliography search of prominent review articles, 42 articles were considered for eligibility. Of those, 6 were

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removed for being irrelevant to the topic, leaving 36. Together these searches resulted in a total of 53 studies that pertained to the different methodologies, devices, and techniques of sanitization in relation to superficial fungal infections of the feet, including basic sanitization^{15–24}, antifungal and antimicrobial materials^{25–35}, sanitization chemicals and powder^{15,16,36–38}, laundering^{39–52}, sanitization putty⁵³, ultraviolet^{54–58}, ozone^{59–62}, non-thermal plasma⁶³, microwave radiation⁶⁴, essential oils^{65,66}, and natural plant extracts⁶⁷ (Table 1).

Basic Sanitization Methods

Sanitization is a key factor in the prevention of fungal infection, spread, and recurrence. In general, discarding old, infected shoes or socks is recommended to help prevent the spread or recurrence of superficial fungal infections^{15,16}. Basic personal hygiene should be maintained by daily and thorough washing and drying of feet^{17–21}, changing socks regularly²², and the cleaning of any presumed modes of transmission (clothing, fomites, and surrounding environment) is also strongly encouraged^{21,23}.

In diabetic individuals washing the feet daily may reduce the risk of onychomycosis¹⁸. There was a significantly lower chance of having onychomycosis in those who reported washing their feet every day, as compared to those who reported not washing their feet daily¹⁸.

A number of studies examined the impact of cleanliness and sanitization of the carpets and washing areas in public locations^{20,21,23}. Regular vacuuming, carpet shampooing, washing

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of floors ^{21,23}, proper foot hygiene, and complete drying of feet ²⁰ helps to significantly reduce the presence of fungi and decrease the fungal spread.

Swimming facilities are often sites of fungal growth and spread. The key to reduction of dermatophyte load is to clean the floors as often as possible ²⁴.

Antifungal and Antimicrobial Materials

A number of antifungal and antimicrobial materials exist which can be effective for the sanitization and prevention of superficial fungal mycoses ^{25–32,34}. Copper has potent biocidal effects ⁶⁸. It was introduced into textiles for odor and microbial control ^{25–28}. When its effectiveness against *Candida albicans* was tested by exposing the fungus to a control fabric or 20% copper fabric for 0-60 minutes, the copper led to a significantly reduced number of viable fungi, with reduction increasing with time, as compared to the control fabric ²⁵. When provided to miners trapped in a cave of high temperature and humidity, they reported that wearing copper-impregnated socks led to a significant reduction in discomfort, irritation, dry skin, and scaling, as well as a marked decrease in foot odor, even after having been trapped for 36 days before receiving the socks ²⁶.

In a study that examined the use of copper-impregnated socks of soldiers, who often wear occlusive footwear for long periods of time, providing optimal conditions for fungal foot growth, a reduction in symptoms of superficial mycoses occurred after wearing the socks for 3

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weeks²⁷. Fifty-three soldiers were provided with 20% polyester yarn socks impregnated with 1% copper oxide to be worn daily. After 3 weeks a questionnaire about the effectiveness of the socks indicated reduction in skin irritation, itching, dryness, and foot and sock odor, showcasing the effectiveness of the copper ions contained in the socks to act as a biocide²⁷. Another study found that even when worn daily and laundered up to 30 times, socks with 12% copper oxide impregnated polyester fibers (with a weight/weight of copper oxide content per fiber of 1%) retained their biocidal efficacy against *Trichophyton mentagrophytes*, *T. rubrum* and *C. albicans*²⁸.

There have been numerous studies to evaluate the efficacy of chemical treatments of textiles against fungal growth. Shirakawa showed that shoes assembled using an adhesive containing sodium- and calcium-pentachlorophenate inhibited growth of *T. rubrum*, *T. interdigitale* and *T. gypseum*. This chemical treatment was found to inhibit fungal growth, even after the shoe sole had undergone continuous washing for 24 hours^{29–31}. Hammer et al. examined the effects of fabric finished with copper against *T. mentagrophytes*, *T. rubrum* and *C. albicans*, along with didecyltrimethylammonium chloride (DDAC), poly-hexamethylenbiguanide (PHMB), and two silver chloride concentrations (AgCl low and high)³². All tested compounds showed inhibition of *C. albicans* growth, but AgCl low concentration was found to be the most effective. *T. mentagrophytes* was unaffected by DDAC, while *T. rubrum* showed complete inhibition. *T. rubrum* was also more susceptible to PHMB than *T. mentagrophytes*, but was less

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susceptible to low concentration AgCl ³². These findings show that although inhibiting effects of antimicrobial materials are seen, it does not indicate a universal suitability for the efficient control of dermatophytes.

Another study examined the potential antifungal effects of non-woven textiles containing PHMB when mixed with sophorolipid ³³. Four volunteers who showed no signs of tinea pedis (as confirmed through visible examination and culture method) and had no immunosuppression placed their feet on paper soaked with 60 mL of normal saline that had one streak of *T. mentagrophytes* cultured in an agar plate. This process was repeated four times per individual. Feet were washed immediately after either with soap, using a non-woven textile impregnated with PHMB and 0.1% sophorolipid, or using a non-woven textile soaked in tap water (in the control condition feet were not washed) ³³. Washing with the PHMB textile was found to significantly reduce the colony forming units of fungi to an equivalent level of washing with soap ³³.

In a double-blind, randomized, placebo-controlled study, the treatment of tinea pedis using hygienic socks loaded with antifungal microcapsules was assessed ³⁴. Special hygienic socks with a 5-toe design were sprayed inside with prepared 1.55-g clotrimazole-loaded microcapsules. Forty-two patients randomly received 14 pairs of the clotrimazole-loaded socks or control socks. Clinical and mycological assessments were performed at 0 and 2 weeks, and then after a 2-week maintenance phase without treatment ³⁴. At 2 weeks, the clotrimazole-

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loaded socks had a significant antifungal effect with 77% of the active group being clinically and mycologically cured, versus 36% of the control group. After 2 weeks of maintenance following treatment, improvement was sustained in those that were cured. Overall, cure rate was also sustained during a final follow up at 4 weeks ³⁴.

In 2015, a study was performed to determine if diabetic foot infection could be prevented through the use of modified cotton socks ³⁵. Four sets of socks were made on a single knitting machine. Socks made from pure cotton (control) yarn were compared to socks made from cotton yarn blended either with crushed volcanic materials, activated carbon, or tribomechanical activated zeolite. All modified socks showed significant antimicrobial activity against *C. albicans*. After wearing the socks for 10 hours, diabetic patients also reported no sweating or odor for all modified socks, as compared to the pure yarn socks ³⁵.

Sanitization Chemicals and Powders

Gupta et al. found that a powdered 250mg terbinafine tablet (prepared to create a 0.1% stock solution in 80% ethanol) led to a complete elimination of *T. mentagrophytes*, *T. raubitschekii*, and *T. tonsurans* after only 15 min of exposure ³⁶. Other research has found that *PVP-I* povidoneiodine, *PHMB-B* polyhexamethylene biguanide-betaine, and *OCT-D* octenidine dihydrochloride are fungicidal against *C. albicans*, *PVP-I* and *OCT-D* are similarly fungicidal

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against both *T. interdigitale* and *T. rubrum*, but that PHMB-B is only fungicidal against *T. interdigitale* (and not *T. rubrum*)¹⁷.

Sanitization (antifungal) powder has been recommended for the removal of infectious fungal elements from shoes^{15,16,37}. Antifungal powders that contain miconazole, clotrimazole or tolnaftate, when applied to either the shoes or directly to the feet, are reported to reduce the chances of recurrence of onychomycosis¹⁶. A study examined the use of a 1% terbinafine powder or spray to treat the insoles of shoes that had been colonized by skin scales infected with *T. rubrum*³⁷. Felt, latex, and leather insoles were all examined, with cultures being taken 48 or 96 hours after the powder or spray was applied. It was found that the dermatophyte could no longer be cultured 48 hours after a single application and remained sterile for 6 weeks³⁷.

However, not all results have shown antifungal powders to be an effective method of preventing onychomycosis. Warshaw and St. Clair tested a miconazole powder 2% in a double-blind, placebo-controlled, randomized study that took place over 2 years, including 48 patients with clinical and mycological cure of onychomycosis for at least 1 year, but no longer than 36 months³⁸. Patients used the miconazole powder on their feet and in their shoes biweekly throughout the study, and were evaluated in person at the start of the study, at 1 year, and at 2 years (and were contacted by phone at 6 and 18 months to evaluate compliance or possible side effects)³⁸. No significant differences were found between the active and the control

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groups in terms of reinfection, time to reinfection, patient assessment of “worse” condition at any point throughout, or percentage with athlete’s foot ³⁸.

Laundering

Bacteria and fungi that survive the laundering process are the main source of malodors which occur due to the continually moist environment. Bacteria can grow both in the washing machine itself and on the textiles laundered within ³⁹. Fungal pathogens (including *Candida* and *Fusarium* spp.) can also be found in washing machines, particularly within the drawers for detergents and rubber door seals ⁴⁰. A number of factors influence the presence of fungi and its colonization, including the use of mild detergents and softeners, washing temperature ⁴⁰, and washing time ^{41,42}. Regularly cleaning the washing machine and its components, as recommended by the manufacturers, is key to helping prevent the further spreading of superficial mycoses. Machine washing is superior to hand washing, as the physical actions of the washing cycle (e.g., drum agitation) assist in reduction of many bacterial and fungal organisms ⁴³.

Another study that examined the impact of the actual laundry machine on the washing outcome tested out a silver laundry machine that electrically generated silver ions ⁴⁵. As compared to a regular laundry machine, the silver machine was found to be effective against most fungi regardless of detergent use, but when detergent was used almost all fungi were

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eliminated. The cleaning action of the silver laundry machine with detergent was found to be higher than that of a regular laundry machine, with a significant reduction in *T. rubrum*, *C. albicans*, *Microsporum canis* and *Aspergillus flavus* after the final spin cycle. In the absence of detergent, an equivalent reduction of fungi was seen, with the exception of *A. flavus*. In comparison, without detergent the regular laundry machine only resulted in reductions to *T. rubrum* and *C. albicans* ⁴⁵.

Past research had indicated that laundering alone was not enough to eliminate fungus ⁴⁴, however recent research has shown that it can significantly reduce fungal load. Basic methods of washing socks can impact dermatophyte load. It has been found that turning socks inside-out to wash them can lead to better removal of dermatophytes ⁴⁶. It is also important to wash infected textiles separate from uninfected laundry, as up to 16.1% of a *T. rubrum* spore load from infected laundry can be found in the rinsing water of the last rinse cycle, indicating the potential for cross-contamination between textiles ⁴¹. Using appropriately high water temperatures (at least 60°C) for laundering is also integral, and a common agreement across the literature ^{40–42,47,48}. Laundering textiles and footwear at 60°C can significantly decrease, or eliminate entirely, dermatophyte colonies and other causal organisms within the materials ^{40–42,47,48}. As laundering temperature decreases, antibacterial and antimicrobial effectiveness decreases, and longer washing cycles are required for the removal of microbials, including *C. albicans* (but with the exception of *T. mentagrophytes*, which can be counteracted with the

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addition of activated oxygen bleach [AOB])⁴². It has been found that after washing for only 10 min at 30°C, *C. albicans* can no longer be detected in clothing; however, washing for 45 min at 60°C fully eradicates both *C. albicans* and *T. rubrum*⁴¹. A minimum wash time of 45 min at 46.7°C can significantly reduce *T. mentagrophytes*, a higher temperature required than for similar reductions of *Staphylococcus aureus*, *Enterococcus hirae*, or *C. albicans*⁴². Lower laundering temperatures may reduce the fungal load (and even eradicate *Candida* spp.^{41,47,49} and *M. canis*⁵⁰); but the eradication of most dermatophyte pathogens requires higher temperatures. Lower temperatures can be aided in antifungal action by the process of tumble drying⁴⁹, ironing⁵¹, sun exposure⁵², or the use of bleach⁴³ or AOB^{42,48} (Figure 2).

Sanitization Putty

There has been one study where the efficacy of a sanitization putty at reducing bacterial and fungal contamination of footwear was assessed⁵³. It was concluded that the sanitization putty was effective as an antibacterial but not as an antifungal⁵³.

Ultraviolet

A number of studies have evaluated the effects of ultraviolet (UV) radiation as a sanitization method for fungi⁵⁴⁻⁵⁸. In a study that examined the inactivation of dermatophytes by ultraviolet C (UV-C), it was found that *Epidermophyton floccosum* was the least susceptible to

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UV-C irradiation, followed by *T. mentagrophytes*, and *T. rubrum*; *M. canis* was the most susceptible ⁵⁴.

When directly examining the use of a commercial UV shoe sanitizer for the decontamination of cultured dermatophytes in footwear, leather and athletic shoes were inoculated with either *T. mentagrophytes* or *T. rubrum* ⁵⁵. They were then stored at 35°C for 4-5 days, irradiated with 1 to 3 cycles of radiation, and specimens were obtained from the inner surfaces of the shoes and cultured ⁵⁵. For *T. mentagrophytes*, the reduction percentages for one, two, and three cycles were 83.9%, 77.6%, and 85.4%, respectively. For *T. rubrum*, the reduction percentages for one, two, and three cycles were 88.8%, 75.6%, and 68.43%, respectively. Overall, UV-C treatment of shoes was found to be effective for sanitization and reduction of fungal colonies ⁵⁵.

Cronin and colleagues investigated which wavelengths within the UV spectrum inhibited the growth of *T. rubrum* ⁵⁶. Wavelengths between 280 and 400 nm (UV-C to UV-A) were investigated. It was found that exposure at 280 nm was inhibitory, and no growth of *T. rubrum* was seen following a 2-week incubation. However, exposure to wavelengths longer than 280 nm was not inhibitory. These findings indicate that UV-C light could be an effective method of decontamination of *T. rubrum* from reservoirs, such as shoes ⁵⁶.

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Ozone

Gupta and Brintnell first examined the efficacy of ozone gas as a sanitization technique on footwear contaminated with fungal material in 2013⁵⁹. Swabs taken from footwear of onychomycosis patients were cultured. In 80% of test cases at least one piece of footwear per patient cultured dermatophyte fungi, nondermatophyte molds, yeasts, or a combination of organisms. Footwear was exposed to a cycle of ozone gas through either passive or directed means in the absence or presence of concurrent heating, respectively⁵⁹. In 87.5% of experiments there was a reduction of viable organisms after exposure to ozone gas. Overall, ozone gas was found to be effective for sanitizing contaminated footwear from onychomycosis patients⁵⁹.

In subsequent work, Gupta and Brintnell further assessed the fungicidal capacity of ozone gas on *T. rubrum* and *T. mentagrophytes* specifically⁶⁰. Three types of cultures were used: actively growing agar cultures, agar cultures freshly inoculated with defined numbers of fungal conidia, and agar and liquid cultures inoculated with sterile gauze. The culture/seeded gauze was placed inside a commercial ozone gas sanitization device and exposed to a cycle of ambient air evacuation and replacement by ozone gas to an amount maintained throughout the cycle, followed by defined time periods of exposure to ozone and ozone neutralization⁶⁰. *T. rubrum* cultures were no longer viable following a standard cycle, regardless of culture concentration. *T. mentagrophytes* retained limited viability following one cycle, but this was

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dependent upon the concentration of the culture. Overall, the standard cycle of ozone exposure in the commercial device was > 99% fungicidal to *T. rubrum* and *T. mentagrophytes* ⁶⁰.

Both gaseous ozone and ozonized oil were evaluated as germicidal agents against *M. canis*, *M. gypseum*, *T. rubrum*, *T. mentagrophytes*, and *T. interdigitales* ⁶¹. It was found that, overall, ozonized oil contained a higher toxicity level than gaseous ozone. The minimum inhibitory concentration (MIC), the lowest ozonized oil concentration that reduced growth or spore germination by 80%, was determined for each fungus. When the MIC of ozonated oil was applied, there was a steady reduction in sporulation of *M. gypseum* and *M. canis* (98.7% and 97.1%, respectively). *T. rubrum* showed the least reduction in sporulation (72.6%) ⁶¹.

In a more recent study it was found that ozone gas was effective at eradicating *C. albicans* in yeast form, and inhibiting germ tube formation ⁶². As ozone exposure time increased, biofilm production decreased significantly. These findings show implications for using gaseous ozone in disinfecting footwear, as it will contain *Candida* spp., but may require up to 60 min of exposure for efficacy ⁶².

Other Methods

The efficacy of using non-thermal plasma (NTP), via a low-temperature atmospheric-pressure plasma jet (APPJ) as a sanitization device against *T. interdigitale* in shoes was examined ⁶³.

Shoes from a patient with chronic tinea pedis (1 sport pair, 2 leather pairs) were swabbed for *T.*

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interdigitale, and confirmed by culture. The inside of each shoe was then irradiated by the APPJ by moving the jet over the entire inner surface of the shoe for 3 min. Afterwards, all insoles were swabbed again and the swabs were streaked onto agar and incubated over 6 weeks at 30°C⁶³. After 6 weeks it was found that all insoles treated with the APPJ showed no fungal or bacterial growth, indicating that non-thermal plasma irradiation can eradicate fungal contamination in shoes⁶³.

The effects of microwave radiation on *T. rubrum*, *T. rubrum* var. *nigricans*, *T. interdigitale* and *M. canis* in infected polyethylene sponge and cork shoe insoles were examined⁶⁴. It was found both insole types showed a significant effect by the microwave radiation, with complete growth inhibition of all four dermatophytes after 30 seconds of exposure at 560 W (maximum temperature of 60°C), without causing damage to the insoles themselves⁶⁴.

The efficacy of thyme oil (from *Thymus vulgaris* L.) on textiles with phase change materials (which provide a thermoregulation system) against *T. rubrum* and *C. albicans* was examined⁶⁵. Materials treated with 20µL/mL of thyme oil showed antifungal activity against both *T. rubrum* and *C. albicans*⁶⁵, indicating that thermoregulating materials treated with thyme oil may help prevent superficial mycoses. Additionally, thyme oil applied as an 8% concentration in methanol to linen-cotton blended fabric has a strong antifungal and antibacterial effect⁶⁶.

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Another method that has been examined was the use of natural fungicide extracted from neem (*Azadirachta indica*) leaves and mahogany (*Swietenia Mahagoni*) fruit bark ⁶⁷. Fungus was taken from a shoe, cultured in Sabouraud Dextrose Agar (SDA) plate, and then used to test the antifungal efficacy of the extracts. The fungicidal extracts were mixed with shoe polish, and then compared to shoe polish only (non-fungicidal) ⁶⁷. The fungicide-shoe polish mixtures inhibited the growth of fungus, and did not show fungal growth for 1 month (versus the plain shoe polish, which showed fungal growth within 3 days) ⁶⁷.

Discussion

Limitations of Previous Studies

There are numerous methods of sanitization of footwear or textiles from dermatophytes. However, there are limitations (Table 2). Copper-oxide impregnated socks seem like an optimal suggestion, particularly for those that may have difficulty with regular, proper hygiene, but randomized controlled trials have not been performed ^{26–28}.

The regular application of antifungal powder in shoes is a common suggestion throughout the literature. Only two studies have evaluated the use in shoes ^{37,38}, both of which examined different antifungal compounds resulting in one seeing a significant effect of the powder (1% terbinafine) ³⁷ and one of which no significant results were found (miconazole 2%) ³⁸. Most recommendations of antifungal foot powder in shoes are based on treatment of similar

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compounds applied directly to feet. An effective antifungal compound for the feet would also need to demonstrate efficacy against shoes; controlled studies are required to demonstrate efficacy in disinfecting shoes.

The recommended temperature for laundering clothes for complete dermatophyte eradication is a minimum of 60°C^{40–42,47,48}. However, the current trend of laundering is to use cold water to save energy and remain environmentally friendly. As well, some clothing items are not supposed to be washed in high temperatures, as it may cause shrinkage. An alternative could be to wash socks, stockings, or other washable footwear in a separate laundry load, but often this would not be enough clothing for a full load. As discussed, certain factors can be implemented to mitigate the lessened antimicrobial effect of lowered washing temperatures. However, not all of these are optimal options either. Bleach is recommended when lowered washing temperatures are used to help eliminate dermatophytes, but bleach can be dangerous if not used appropriately and with the proper safety precautions. As well, many textiles can be irreparably damaged by the use of bleach. Whenever possible, tumble drying can also help by adding heat to the laundering process. Again, this is not always available.

Proposed sanitization devices such as ozone sanitizers, microwaves, and plasma jets have been found to effectively decontaminate infected footwear of dermatophytes^{59,60,63,64}. However, such machines are not often publicly available, and when they are, the price can be out of range for the average individual. There has been a recent increase in ozone sanitization

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devices on the market; however, these are mostly presented for use on smaller items (such as cell phones). In the case of microwaves, which are often found in the average kitchen, it is unlikely that patients would wish, and they should not, to put their contaminated footwear into a device used for food preparation.

Future Directions

Research has been performed on ketoconazole (KZ) on cotton wound dressings for fungal skin treatment⁶⁹. Cotton wound dressings were impregnated with the KZ, and then tested against *C. albicans*, *Aspergillus niger*, *E. coli*, and *S. aureus*. It was found that KH impregnated cotton wound dressings were a good antifungal⁶⁹. This method has not yet been tested on any textiles used for regular wear, such as socks; however, there is potential for KZ impregnated materials to help prevent superficial mycoses.

Ozone as a sanitization option for footwear may be expanded to sanitizing larger areas⁷⁰. It was found that with 60 minutes of ozone exposure, inactivation of fungi occurred (whereas bacteria viruses only needed 20 minutes, and molds less than 2 minutes)⁷⁰.

Microwave radiation has been shown to be effective for sanitization of dermatophytes within shoes⁶⁴, but further study is required. More research on the impact of microwave radiation on socks and textiles, as well as more studies on shoes, would build upon the current

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promising findings. As well, testing microwave sanitization effects using standard microwave devices available to the public could help bring this method to more households.

Studies of non-thermal plasma (NTP) have performed *in vitro* tests on *T. rubrum*, *M. canis*, and *C. albicans*, *C. glabrata*, and *C. krusei*, although not on shoes^{63,71,72}. NTP was found to be an effective antimicrobial against *T. rubrum*, *M. canis*, and *C. albicans*^{63,71}. It has also been shown to have a fungistatic effect against *Candida* biofilms (*C. albicans*, *C. glabrata*, *C. krusei*) *in vitro*⁷². More research into the use of NTP on textiles would help determine the effectiveness of this technology in sanitizing footwear and textiles.

Conclusions

In order to properly manage onychomycosis, it is necessary to think beyond treatment of the nail, as fungal infections entering the nail unit enter through the skin. Subjects with onychomycosis invariably have tinea pedis, whether or not it is symptomatic or has clinical manifestations. Looking for tinea pedis, and treating it early, is key to prevention. However, those prone to, or at risk for, onychomycosis (for example, diabetics and those with peripheral vascular disease) need to look at their environment as well, including shoes, socks, floors that individuals walk on, shower stalls, and close family contacts. Subjects that live in group homes or use communal facilities are particularly at risk. For optimal management of onychomycosis proper sanitization measures must be implemented.

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Table 1. Sanitization techniques covered in the currently available literature.

Sanitization Techniques	
Established Methods	
Discard old, potentially infected footwear	Dixon (1924); Ameen et al. (2014)
Change socks regularly	Cohen et al. (2005)
Wash feet daily, dry fully after washing	Milles et al. (1998); Raboobee et al. (1998); Iklit et al. (2005); Takehara et al. (2011)
Wash and vacuum floors regularly	Raboobee et al. (1998); Hilmarsdotti et al. (2005); Alsaif et al. (2020)
Disinfect socks, shoes, textiles	Tanaka et al. (2006)
Copper imbued fabric	Borkow & Gabbay (2004); Zatcoff et al. (2008); Borkow (2012); Hammer et al. (2012); Borkow (2013)
Antifungal textiles	Zatcoff et al. (2008); Borkow (2012); Borkow (2013); Yuen et al. (2013); Sanada et al. (2014); Tarbuk et al. (2015)
Terbinafine as antifungal agent	Gupta et al. (2001); Feulihade de Chauvin (2012)
Laundering temperature of 60°C minimum	Hammer et al. (2011); Amichai et al. (2013); Honisch et al. (2014); Babič et al. (2015); Schages et al. (2020)
UV light for sanitization	Dai et al. (2008); Ghannoum et al. (2012); Cronin et al. (2013); Nematolhai et al. (2015); Cadnum et al. (2018)
Gaseous ozone for sanitization	Gupta & Brintnell (2013); Gupta & Brintnell (2016); Zargaran et al. (2017)
Other Methods	
Non-thermal plasma (NTP)	Daeschlein et al. (2011)
Microwave radiation	Budihardja & Mayser (2014)
Essential thyme oil	Walentowska & Foksowicz-Flaczyk (2013); Scacchetti et al. (2017)
Neem leaves and mahogany fruit bark extract	Mamun et al. (2019)

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Table 2. Limitations of the sanitization techniques in the currently available literature.

Sanitization Limitations	
Discard old, potentially infected footwear	May not be feasible financially for all patients
Wash feet daily, dry fully after washing	May be difficult or impossible for certain at-risk individuals (e.g. elderly)
Wash and vacuum floors regularly	May be difficult or impossible for certain at-risk individuals (e.g. elderly)
Copper impregnated socks	Current research does not have randomized trials
Antifungal foot powder	Not enough tested research; only 2 studies with different agents tested
Laundering temperature of 60°C minimum	Environmentally friendly (and often encouraged) to use low temps; high washing temps can damage some clothing
Bleach or activated oxygen bleach	Can be damaging to textiles; can be dangerous if not used appropriately
Tumble dry wet clothing	Not always accessible; tumble dry can damage some clothing
UV light for sanitization	Not accessible to the average individual, with the exception of sunlight (not an effective fungicide on its own)
Gaseous ozone for sanitization	Not accessible to the average individual
Non-thermal plasma (NTP)	Not accessible to the average individual
Microwave radiation	Although average microwave could be used, should not place infected shoes in an apparatus used for food; unreasonable to expect people to have a separate microwave for shoes/socks

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Figure 1. Flow diagram of the search and elimination process used in this review, based on the PRISMA guidelines ⁴.

Fig. 1

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Figure 2. Suggested Laundering Cycle: Turn socks inside out before washing. Launder textiles at a minimum temperature of 60°C, if possible for 60 minutes, or with bleach or activated oxygen bleach (AOB) if using lower temperatures. Tumble dry wet laundry.

Fig. 2