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Introduction to Visible Light Disinfection

What Is Visible Light Disinfection?

Visible Light Disinfection (VLD) is a relatively new disinfection method that utilizes the phototoxic effect of 405 nm visible blue light. Researchers at the University of Strathclyde in Glasgow, Scotland discovered 405 nm light could kill bacteria and other microorganisms which led to an international patent for visible light disinfection granted in 2007. Since this discovery, a number of researchers have done additional studies to explore and understand the use of 405 nm light for disinfection in a number of different applications.

The figure below shows the wavelengths for ultraviolet (UV), visible, and infrared ranges of light. As can be seen, 405 nm is at the low end of the visible light range – hence the name Visible Light Disinfection. 405 nm light is not in the UV light range. The range for UV light starts at 400 nm and goes down to 100 nm. The UV range is typically further divided into the three ranges – UVA, UVB, and UVC as shown in Figure 1

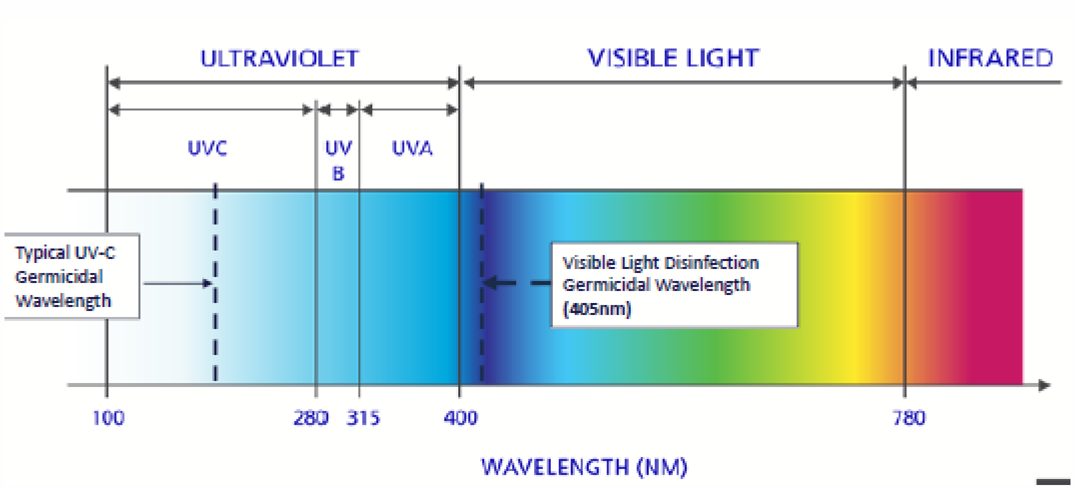

Figure 1

Although UV light and 405 nm light are found close to each other on the electromagnetic spectrum, their actions in microorganisms are quite different. 405 nm light is typically not as effective in killing bacteria as UV light since it works via an indirect mechanism which is described in a later section. However, 405 nm light has the significant advantage of increased human safety due to its lower photon energy. UVC light (around 265 nm) is strongly germicidal but also dangerous to humans. All the UV wavelengths (UVA, UVB and UVC) can cause a wide range of detrimental effects to human skin and eyes. Wavelengths in the visible spectrum can also have harmful effects on the eyes when used at high irradiance levels. However, light at 405 nm, like all visible light, is benign compared to UV wavelengths. If used at appropriate irradiance levels, it can be both germicidal and safe for human exposure.

After the initial discovery that 405 nm light can kill bacteria, many studies were conducted in the following years to understand the range of microorganisms that are susceptible to 405 nm light. The studies included a wide variety of dangerous bacteria such as *Staphylococcus aureus*, methicillin-resistant *S. aureus* (MRSA), *S. epidermidis* and *Escherichia coli* (Guffey and Wilborn, 2006; Maclean *et al*., 2008a; Maclean *et al.*, 2009). Figure 2 lists the range of organisms that have shown susceptibility to 405 nm light.

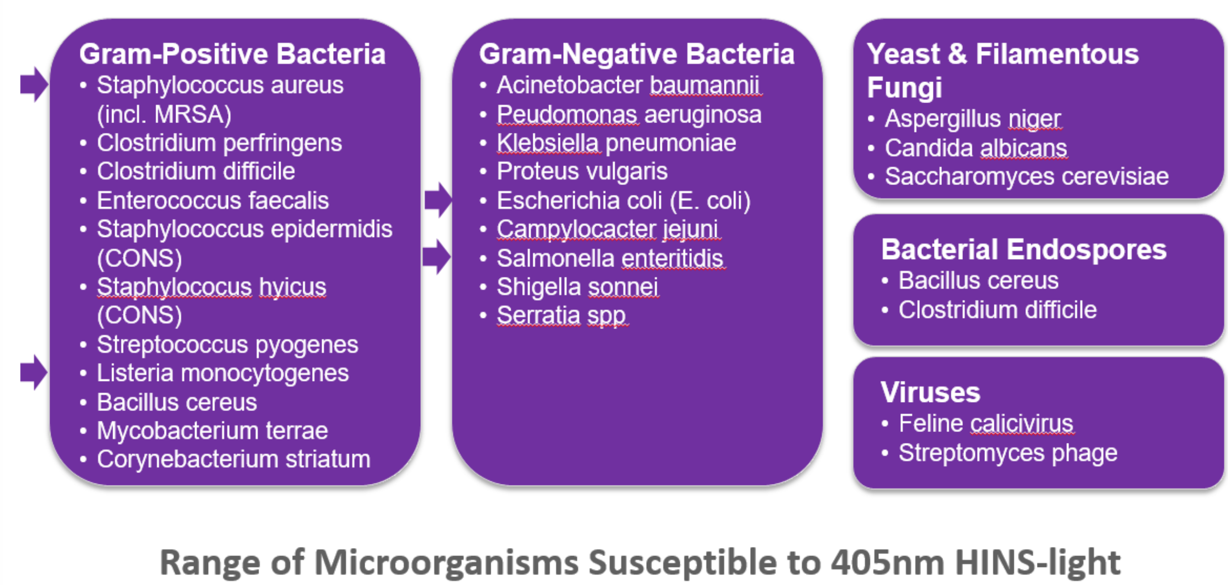

Figure 2

Figure 3 shows actual test results for Staphylococcus aureus and Salmonella enterica with a constant irradiance of 0.5 mW/cm2. Note that the time required can vary for different microorganisms, but both were almost completely inactivated by this level of 405 nm light in less than half a day.

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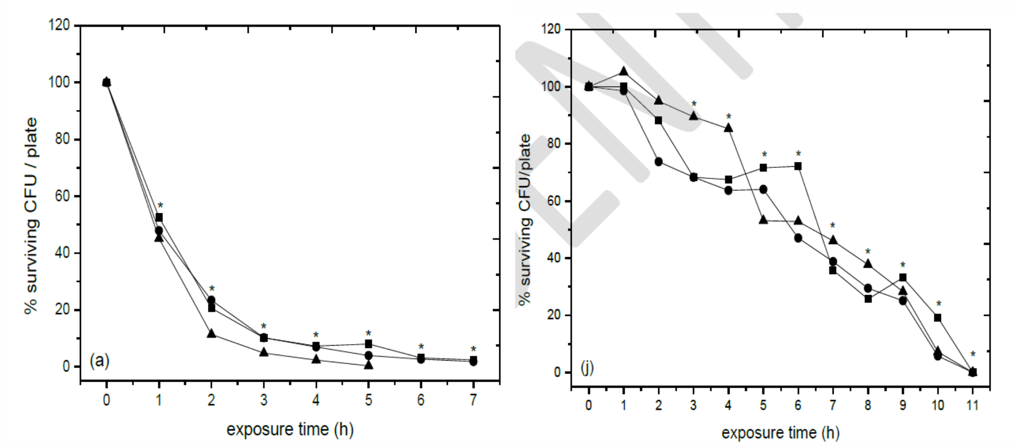

Staphylococcus sureus   Salmonella enterica

Figure 3

In addition to the research done on which microorganisms are susceptible to 405 nm light, test have been conducted with these pathogens on a range of different surfaces. Figure 4 shows some of the results from these tests. The 405 nm light was shown to be effective on all the types of surfaces tested.

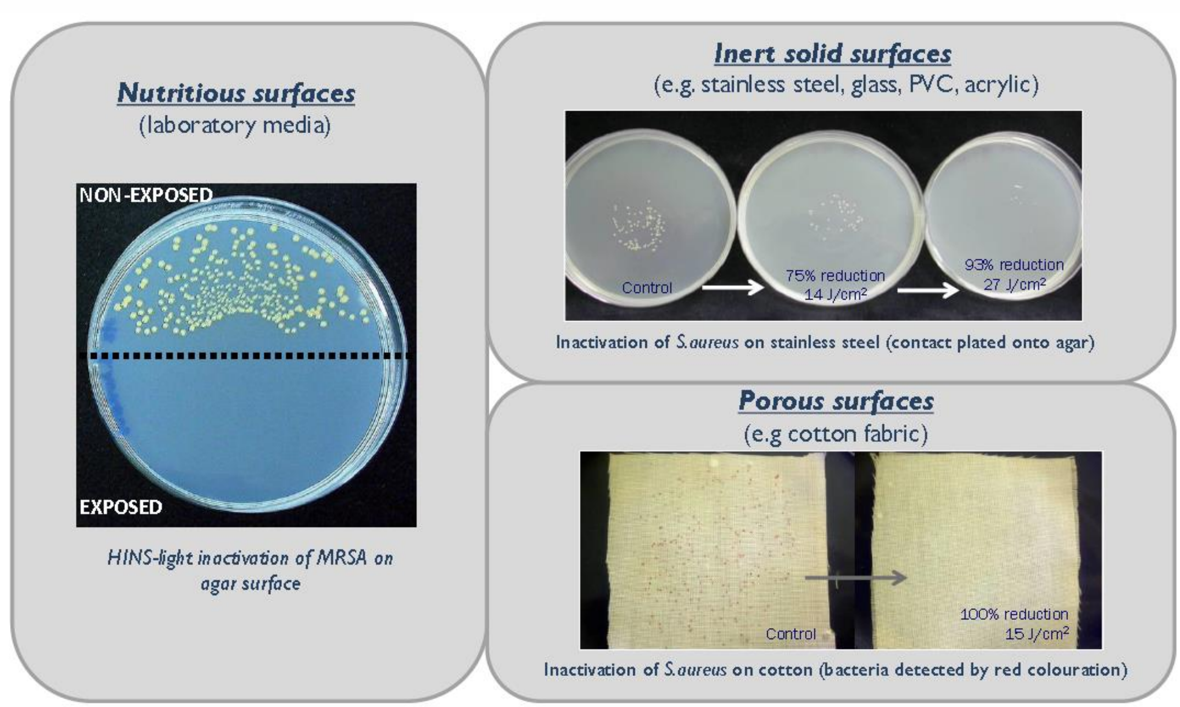

Figure 4

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Another study looked at the effect of 405 nm light on biofilms which are typically experienced as slimy layers on living or non-living surfaces. Biofilms may be found in natural, industrial, and hospital settings. A biofilm is a community **of** bacteria that attach to a surface by excreting a sticky, sugary substance that encompasses the bacteria in a matrix. Biofilms are all around us, in streams, in drains, in fish tanks, and even on our teeth. A biofilm can be composed of a single species or a conglomerate of species. In many cases, biofilms are only bacteria, but they can also include other living things, such as fungi and algae, creating a microbial stew of sorts. Biofilms are complex systems that are sometimes compared to multicellular organisms.

Researchers at the University of Strathclyde conducted a laboratory based experimental study to investigate the bactericidal effect of 405 nm light on E. coli biofilms of varying maturity that were generated on glass and acrylic surfaces. The study also investigated the effect of 405 nm light on biofilms of other bacteria including P. aeruginosa, S. aureus and L. monocytogenes. Results from this study demonstrated the successful inactivation of biofilms on both glass and acrylic surfaces, and that the bactericidal effect was observed with both juvenile and mature biofilm populations. Successful inactivation of bacterial biofilms on the underside of the glass and acrylic surfaces was also shown, demonstrating the ability of 405 nm light to be transmitted through these transparent materials while maintaining its antimicrobial activity.

In addition to rigorous laboratory testing where the bacterial conditions and 405 nm light dosage are carefully measured and controlled, there have been many studies with VLD technology in real world medical applications that show 405 nm light has considerable potential to reduce the environmental airborne bacterial load where people work and play. For example, the use of 405 nm light for environmental disinfection has undergone clinical evaluation in occupied patient isolation rooms in Glasgow Royal Infirmary, where it was used as a background lighting system to provide continuous disinfection of air and exposed surfaces in the presence of patients and staff. The results demonstrated a significantly greater reduction in levels of environmental contamination than was achievable by normal disinfection control methods alone (Maclean et al., 2010). Reduction in the risk of post-operative infection following joint-replacement procedures was demonstrated in a test done at the Maury Regional Medical Center in Tennessee. A 75-80% reduction was recorded in post-operative infections with the use of 405 nm light in the operating room. There is additional evidence from three hospital-based before-and-after studies that 405 nm light was effective at reducing the levels of environmental decontamination in other healthcare settings such as an isolation room in a burn unit and an ICU.

Another area that VLD has been tested is in horticulture. Botrytis cinerea, the cause of grey mold disease, is a very successful necrotroph that kills the host organism and then feeds on the dead matter. It has caused serious losses in more than 200 crop species (Williamson et al. 2007). The pathogen infects leaves, stems, flowers and fruits. The major sources of infection are the air-borne macroconidia that form on branched conidiophores at the end of the infection cycle when the fungus has colonized the host

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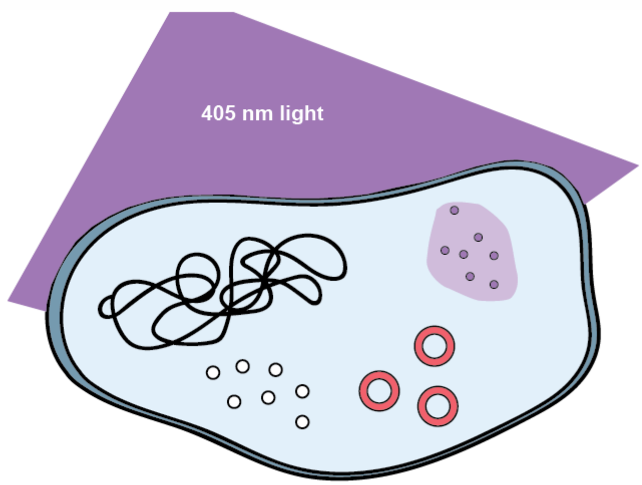
and decomposed the plant tissue (Van Kan 2006; Williamson et al. 2007). The fungus is one of the most economically important postharvest pathogens in many plant species. Chemical control is the primary method used to reduce the incidence of grey mold on major crops because resistant cultivars are not yet available. However, this strategy is only partially successful owing to the development of multidrug resistance in field strains of the fungus (Nakajima and Akutsu 2014). Hence, there is a need to find alternatives to the use of synthetic fungicides. Researchers at Yamiguchi University in Japan have shown in a 2014 study that 405 nm radiation inhibits the growth of botrytis cinerea.

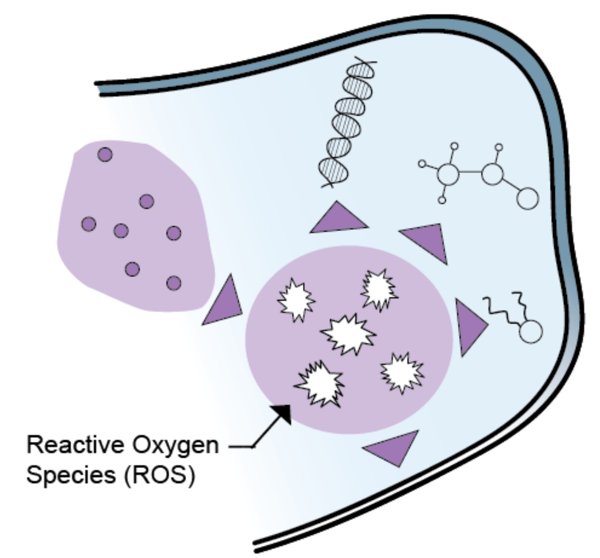
The use of ultraviolet light for surface disinfection of fruits and vegetables in postharvest protection has been studied as well (Ranganna et al. 1997; Marquenie et al. 2002). Several studies have also reported that exposure to ultraviolet-B reduces powdery mildew infections via direct and indirect mechanisms, including a fungicidal effect and induction of plant resistance activities under greenhouse conditions (Keller et al. 2003; Kobayashi et al. 2013). However, ultraviolet light has limitations because of its detrimental effects to workers, such as injury to the skin or eye on direct exposure (Young 2006). 405 nm light does not have this drawback and thus offers a safe alternative to UV light in controlling pathogens on fruits and vegetables.

How does 405 nm light destroy bacteria?

The mechanism of bacterial inactivation is thought to be by photo-stimulation of endogenous intracellular porphyrins, which leads to the generation of reactive oxygen species (ROS). This is illustrated in the diagrams in Figure 5. Numerous studies have been done to better understand and verify this mechanism for how 405 nm light can deactivate bacteria.



Step 1: A porphyrin is exposed to 405 nm light



Step 2: Reactive Oxygen Species (ROS) are then formed that can attack the cell

Figure 5

A porphyrin is a large ring molecule consisting of four pyrroles, which are smaller rings made from four carbons and a single nitrogen. These pyrrole molecules are connected together through a series of single and double bonds which forms the molecule into a large ring. Porphyrins are capable of absorbing certain wavelengths of light, especially when associated with different ions. Porphyrins cause both the red color of blood and the green color of plants. Porphyrin molecules serve a number of purposes in animals, plants, and even bacteria. For this reason porphyrin is considered an *evolutionarily conserved* molecule. This means that because of its usefulness, countless lines of organisms have used and modified porphyrins to fit their needs.

A porphyrin molecule is an organic molecule and must be created and destroyed by specific proteins in the body. Because proteins are programmed by the DNA, any mutations in the DNA can cause malfunctions in the protein which process porphyrin molecules. While usually extremely helpful, a porphyrin which hasn't formed properly or cannot be broken down poses a serious threat to the body. Porphyrin molecules are highly interactive. They can disrupt the cell membrane, and because they hold an iron molecule with the potential to act as an electron sink, they encourage the formation of *free radicals*.

Laboratory studies have shown that a range of light wavelengths in the region of 400-425 nm can be used for bacterial inactivation, but optimal antimicrobial activity has been found at 405 nm. This peak in activity correlates with the absorption maximum of porphyrin molecules which react with oxygen or cell components when exposed to light at this wavelength causing oxidative damage to the cell membrane and microbial cell death.

Bacteria use porphyrins in a similar way to animal cells, although the final molecules they use may look very different from those in animals. Certain bacteria also have the ability to *photosynthesize*, and like plants, they use porphyrins to capture the energy of the sun.

Among the ROS, ·OH is the most potent damaging radical which can react with all biological macromolecules (lipids, proteins, nucleic acids and carbohydrates). It is extremely reactive and can lead to formation of DNA-protein cross-links, single- and double-strand breaks, base damage, lipid peroxidation and protein fragmentation. Bacteria are more susceptible to this oxidative stress than human tissue due to fewer antioxidants and less efficient repair mechanisms.

Research published in 2018 has shown that airborne cells are 3-4 times more susceptible to 405 nm light than samples in liquids or on surfaces. Results demonstrated successful aerosol inactivation, with a 99.1% reduction achieved with a 30 minute exposure to an irradiance of 22 $mWcm^2$.

Advantages of Visible Light Disinfection

While pathogens have been shown to develop resistance to antibiotics, research has not shown any similar reaction to 405 nm light. Other known solutions such as chemical washing are effective only at the time of the treatment – there is no ongoing benefit. 405 nm lighting can remain powered and will therefore act on any pathogens introduced after the time of treatment. Whatever surface or air space the light is illuminating continues to be treated.

VLD does not require any pre-treatment or other material to activate its effectiveness. It is also not impacted by other disinfecting activities. VLD doesn't necessarily require the space to be un-occupied. Disinfection with visible light doesn't depend on a specific procedure or protocol to be followed. A solution can operate automatically as planned providing dependable results. Unlike UV solutions, 405 nm light does not discolor or breakdown materials and surfaces in the space being treated.

405 nm light can be blended into white light and provide a low level of disinfecting while an area is occupied. It can then automatically be switched to a 405 nm only mode when the room is unoccupied providing a higher level of disinfection. 405 nm LED's can be incorporated in a wide range of equipment allowing larger areas as well as specific or isolated areas to be treated. Custom controls can be integrated with any other control equipment that might be present.

Alternatives to Visible Light Disinfection

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While 405 nm light is effective in inactivating a wide variety of pathogens, it commonly is used with other decontamination methods. Below is a list of disinfection technologies used in medical and food processing with their relative advantages and disadvantages.

Manual Cleaning

- PROS
  - Wide antimicrobial efficacy
  - Easy to implement, understood
  - Low material/equipment cost
- CONS
  - Labor intensive w/ compliance issues
  - Only suitable and accessible surfaces treated
  - Air not treated; Fabrics often not treated
  - Short term effect - limited on-going benefit
  - Disinfectants can be toxic
  - Microbial resistance can develop

Fogging (Chlorine dioxide or Hydrogen peroxide)

- PROS
  - Wide antimicrobial efficacy
  - Rapid decontamination effect
  - Surface and Air are treated
- CONS
  - Labor intensive w/ compliance issues
  - Only suitable and accessible surfaces treated
  - Fabrics often not treated
  - Short term effect - limited on-going benefit
  - Disinfectants can be toxic

Steam Cleaning

- PROS
  - Wide antimicrobial efficacy
  - Rapid decontamination effect
  - Good for terminal cleaning
  - Dirt, water and contaminants are vacuum extracted
- CONS
  - Safety issues, requires experienced operators/supervision
  - Space must be unoccupied
  - Short term effect - limited on-going benefit
  - Only suitable and accessible surfaces treated
  - Can't be used on electronics and other equipment

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UV Light

- PROS
  - Wide antimicrobial efficacy
  - Rapid decontamination effect
  - Air and surfaces are treated
  - Good for terminal cleaning
- CONS
  - Utilizes dangerous radiation - humans cannot be exposed
  - Requires operator training/supervision
  - Space must be unoccupied
  - Some materials can be damaged by UV radiation
  - Short term effect - limited on-going benefit

Pulsed Xenon Lamp Technology

- PROS
  - Rapid disinfection
  - Geared for close surface applications
  - Penetrates clear packaging
- CONS
  - Utilizes UV, visible spectrum, and infrared wavelengths – relatively inefficient use of light energy
  - Relatively expensive equipment required
  - Short term effect - limited on-going benefit

Summary

Visible Light Disinfection is an exciting new technology that has already proven to be beneficial to reduce patient infections in healthcare facility field tests. The technology is based on 405 nm light which is in the visible light spectrum and thus is safer than UV-based disinfection solutions. Applications can use 405 nm light on a continuous basis at lower levels to reduce the level of pathogens in an area that people use or can be used at higher levels when people are not present to reduce the level of pathogens in an area in a shorter amount of time. Standard lighting controls can be used to schedule the level and time of 405 nm light as needed for a given application.

Applications in food processing are also currently being explored. These applications typically require testing with specific food complexes and environmental conditions to determine the dosage required. Hubbell Lighting Components can help with developing the light sources and controls needed to test the 405 nm dosage level required for a given application.