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Valorization of biomass to activated carbon for wound dressing applications: Recent trends and future challenges

Paramasivan Balasubramanian [*,1], Mari Selvam S [1]

Department of Biotechnology & Medical Engineering, National Institute of Technology Rourkela, Odisha 769008, India

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A B S T R A C T

Activated carbon (AC) dressings are significantly effective than conventional antibiotic therapy for chronic wounds and associated ulcer treatment. However, comprehensive analysis of the current state of the art and potential oversights of research is limited. This critical review illustrates the features and classification of AC dressings with scientometric analysis to understand research growth and explore existing knowledge gaps. Besides, commercial AC dressings have been described with emphasis on their effectiveness compared to other dressings made of different biomaterials. AC dressings showed higher potential antibacterial effects, biocompatibility, non-cytotoxicity, and tissue growth than commercial dressings when incorporated with antimicrobial agents and/or biomaterials. Anticipating further research on advanced fabrication techniques using various polymers and investigation of the impact of AC on cellular interactions, it was concluded that these findings have promising implications for diverse wound healing applications. Also, well-established long-term experimentation has to be enhanced with combination therapies involving AC for wide acceptance in clinical practice.

1. Introduction

Wound healing is an outcome of the complex interface between various cellular and molecular events in different phases and any disturbances caused during the regulation of these events leads acute wound to chronic (Dhivya et al., 2015; Zhu et al., 2023). To be precise, the factors like drug dosage, treatment, and nourishment through food lead to chronic wound formation and it depends ultimately on a person's health condition for healing wounds (Reinboldt-Jockenhöfer et al., 2021; Melotto et al., 2022; Canchy et al., 2023). The age of the patient, hydration levels, pressure endured by vessels, and improper blood circulation also play a vital role in the extension of the wound closure period (Han and Ceilley, 2017; Viaña-Mendieta et al., 2022). Among various indications affiliated with chronic wounds, malodor, and wound discharges result in biofilm formation and cause major discomfort to patients as well as medical practitioners (Hampton, 2015). Such accompanied odor is mainly due to the bacterial consumption of nourishment within a non-viable wound bed causing excessive drenching and subsequent colonization leading to psychosocial symptoms (Corbett et al., 2020; Morrison et al., 2022). Biofilm formation aids in inflammatory reaction to a certain extent however due to increased fluid discharge later, the bacterial colonization prevailed and impeded the progression to the next phase. Studies stated that *Staphylococcus aureus and Pseudomonas aeruginosa* were the predominant bacteria found on the biofilm (Flanagan, 2013; Wu et al., 2019; Ye et al., 2023). Various *in vitro* and animal studies have been performed on microbial biofilm development associated with chronic wounds (Park et al., 2016; Hunt et al., 2017; Oopath et al., 2023).

Antibiotics were used initially for the administration of chronic wounds owing to the prevalence of bacterial biofilm in 70 % of chronic wound infection cases (Leaper et al., 2015). Intravenous administration of antibiotics such ascefazolin, oxacillin vancomycin, ceftaroline, ciprofloxacin, and tazobactam was utilized to treat patients. However, these antibiotics helped in treating infections rather than healing wounds (Abbas et al., 2015; Yang et al., 2022). Later it was also observed that the resistance developed by microbes to the antibiotic medications gradually directed to the failure of antibiotic treatment (Tzaneva et al., 2016; Perikleous et al., 2023). Alternate treatment options involve the usage of antimicrobial agents in moisture-retentive dressings for effective removal of wound discharge and adsorption of malodor. However, the administration of antimicrobial agents to chronic wounds existed with many limitations wherein the studies conducted were usually of

* Corresponding author.
E-mail address: biobala@nitrkl.ac.in (P. Balasubramanian).
[1] These authors contributed equally.

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shorter periods and lesser sample sizes even with many randomized control trials (Akhmetova et al., 2016; Zhang et al., 2017). Dressings developed with the antimicrobials have limited evidence supporting their effectiveness and its antagonistic after-effects were applied on a smaller scale by medical practitioners.

Activated carbon (AC) is one of the carbonaceous materials obtained through the thermochemical conversion of feedstock like lignocellulosic biomass, agricultural forestry residues, and microalgae in oxygen-less environmental conditions (Pathy et al., 2020, 2021) and then activated through acids/alkali or heated under CO_2/steam atmosphere (Muller, 2021; Chauhan et al., 2023). The conversion of lignocellulosic biomass reduces its negative environmental impacts and thereby less toxicity to human beings (Širić et al., 2022). AC-based dressings were estimated to be the recurrently used and reputable product in the arena of wound welfare. They were widely acclaimed owing to their extensive adsorption capability. The solitary application of AC united the beneficial effects of various dressings and therapies intended for the administration of non-healing wounds (Scheer et al., 2017; Vivcharenko et al., 2023). Chemically modified AC showed significant antibacterial activity at the site of application (Sharifuddin et al., 2019). Numerous studies have indicated that wounds which exhibited minimal response to treatment with antimicrobial agents showed effective administration of AC, without any observed toxicity depending on the type of wound (Murphy, 2016). (Forss et al., 2022) fabricated an AC-based dressing containing agarose film and studied its behavior in reducing the human detection of 2-aminoacetophenone associated with *Pseudomonas aeruginosa* infection and possessed better mechanical properties. (Probst et al., 2022) reported that polyacrylate wound pad dressings with activated carbon cloth exhibited faster reduction of both wound area and maceration area compared to the non-adhesive hydro cellular foam dressing with silver.

There are numerous reviews focussed on controlling the indications caused in the wound healing process. The promises and pitfalls of the different topical agents with their mode of action have been discussed and the benefit of the usage of AC dressing rather than other hydrogel and antiseptic dressings have been elucidated in the studies of da Costa Santos et al. (2010), Akhmetova et al. (2016), and Minsart et al. (2021). Liu et al. (2020) illustrated the utilization of different forms of carbon in wound dressing with emphasis on the characteristics of dressing composite with more focus on the micro/nano carbon structures. Soonmin et al. (2022) have explained the beneficial use of activated carbon in biomedical applications wherein the authors highlighted its use as deodorant, skin care, and for diarrhoea treatments. The reviews emphasizing the importance of the utilization of AC in the fabrication of wound healing material and representation of state of art research are limited.

The present review focuses on the strategies of fabrication of AC dressings along with their characteristics and comparison with other commercialized dressings. This review gives an insight into the development of various forms of AC dressings employed for the wound healing process. To the best of the author's knowledge, scientometric analysis of the progress of activated carbon in wound healing applications has not been documented so far. Further, proper categorization of AC dressings based on different factors is very limited and has been reported in this manuscript with its extensive utilization in the administration of wounds. The main aim of the current study is to answer the questions: 1) What is the current state of research on activated carbon (AC) dressings for wound healing, and what are the key findings and advancements in this field? 2) What are the different fabrication strategies employed for AC dressings, and how do they influence the properties and performance of the dressings? 3) What are the future directions and emerging trends in the development of AC dressings for wound healing, and what areas of research require further investigation? In summary, this review offers an overview of the current state of research on AC-based dressing, highlighting both current trends and areas of deficiency through scientometric analysis. Furthermore, the review elucidates the mechanism behind the wound-healing activity of AC-based dressings. By addressing these knowledge gaps, this work sets the stage for advancing the emerging research trend and accelerating progress in the field of AC dressing.

2. Methodology

Citespace (5.6. R3) software is one of the science mapping tools that facilitates the high throughput analysis of research trends of a particular subject area. It offers a precise method of producing homogeneous datasets, forming nodes and clusters, and enabling insight into the past and present levels of scientific and technological advancement in a particular field. The result could be transformed into visual graphs which facilitates clear interpretation (Chen, 2006; Yao et al., 2020). The scientometric analysis was performed in Citespace (5.6. R3) software using datasets (publications related to activated carbon dressings) retrieved from scientific databases (Web of Science, Scopus) for the last two decades (2000−2020). The overall adopted methodology for the scientometric analysis and the data interpretation was followed as outlined in the earlier studies of Behera et al. (2022a, 2022b), Nageshwari and Balasubramanian (2022) and Krishnamoorthy et al. (2023). The dataset has been retrieved using a combination of keywords such as "activated carbon", with "dressing", "silver", "nanoparticle", "wound dressing", "wound healing", and "case studies" using boolean operators. The data files obtained from different research databases are processed in the software to obtain compatible uniquely formatted files that could be used for analysing the major contributed countries, authors, and keywords. With the time-sliced parameter selection of the required period and node type (country, author, keyword) available in the software, the collaboration network, and knowledge evolution of the research have been visualized. However, there is the possibility of missing out some countries/authors or other relevant entities due to limitations of datasets or software algorithms.

3. Scientific status of AC-based dressing research

3.1. Analysis of most contributing country in AC-based wound dressing research

The collaboration network of countries involved in the research of using AC in dressing material has been given in Fig. 1a. Over the years, the countries like United Kingdom, Germany, and China have established research collaborations with other countries. Nevertheless, there is a crucial need to expand this collaboration between many countries for bridging the existing research gaps and unlock potentials for further development. As evident from Fig. 1b, China stands first in prominent research contributions on developing AC dressing materials with a centrality score of 0.26. The high-impact research contribution includes investigating the medical use of carbon adsorbents, utilization of nanocomposite hydrogel for biomedical and environmental applications; assessment of bactericidal and cytotoxic properties of silver nanoparticles, and incorporation of antimicrobial nano medicine using graphene materials (Sharma et al., 2018; Liao et al., 2019). The current trend of research includes development of new alternatives for antimicrobials using micro/nano activated carbon fibers that possess excellent biocompatibility and mechanical properties (Nikolaev and Samsonov, 2014; Liu et al., 2020). United States of America (USA) ranks second in research contribution with centrality score of 0.18. The research has evolved from studies on adsorbing fibrinogen using AC cloth dressing with silver and other components (Stucker et al., 2003), to assessing the properties of AC cloth after subjecting to gamma radiation for sterilization (Sekulić et al., 2009), implementation of nanocarbon composites in biotechnological and medicinal perspectives (Bacakova et al., 2020). In India, one of the highest research contributions include the technique of electrospinning with carbonaceous materials for fiber fabrication (Bhardwaj and Kundu, 2010), and incorporation of metal nanoparticle

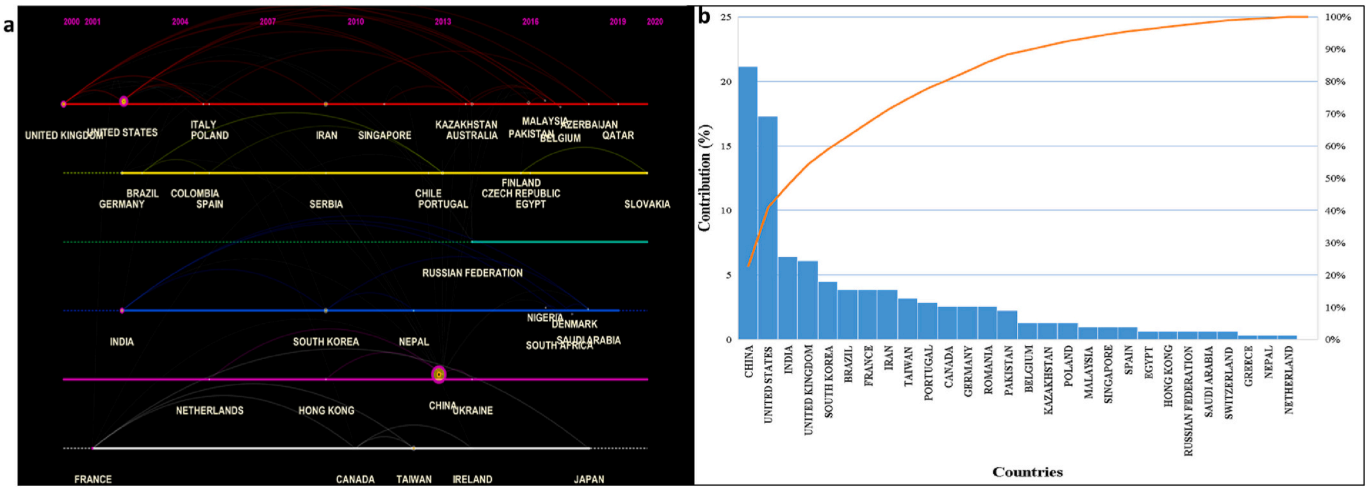

Fig. 1. a) Schematic representation showing collaboration of different countries on the field of AC dressing; b). Pareto chart of contribution of different countries on the publication of research documents on AC dressings.

dispersed carbon nanofibers that could simultaneously control bacterial infection and blood glucose levels (Ashfaq et al., 2017; Bhadauriya et al., 2018). There is a need to accelerate research efforts in certain countries to maximize their high-impact contributions by establishing collaborations with major international partners. By fostering collaborations, these countries can leverage the expertise, resources, and diverse perspectives of their international counterparts, leading to accelerated progress and more significant contributions to research and development.

3.2. Analysis of most contributing author in AC-based wound dressing research

The comprehensive list of authors who have made substantial contributions to advancement of AC dressing research has been given in Fig. 2. The clusters entitled "bacterial cellulose", "advanced bio fabrication strategies", and "modern wound dressing" have higher cluster strength than others and it can be stated that more attention has been given to explore the technologies by the researchers. The cluster network formed by different authors indicates the similarity and correlation of research. For instance, corresponding to bacterial cellulose

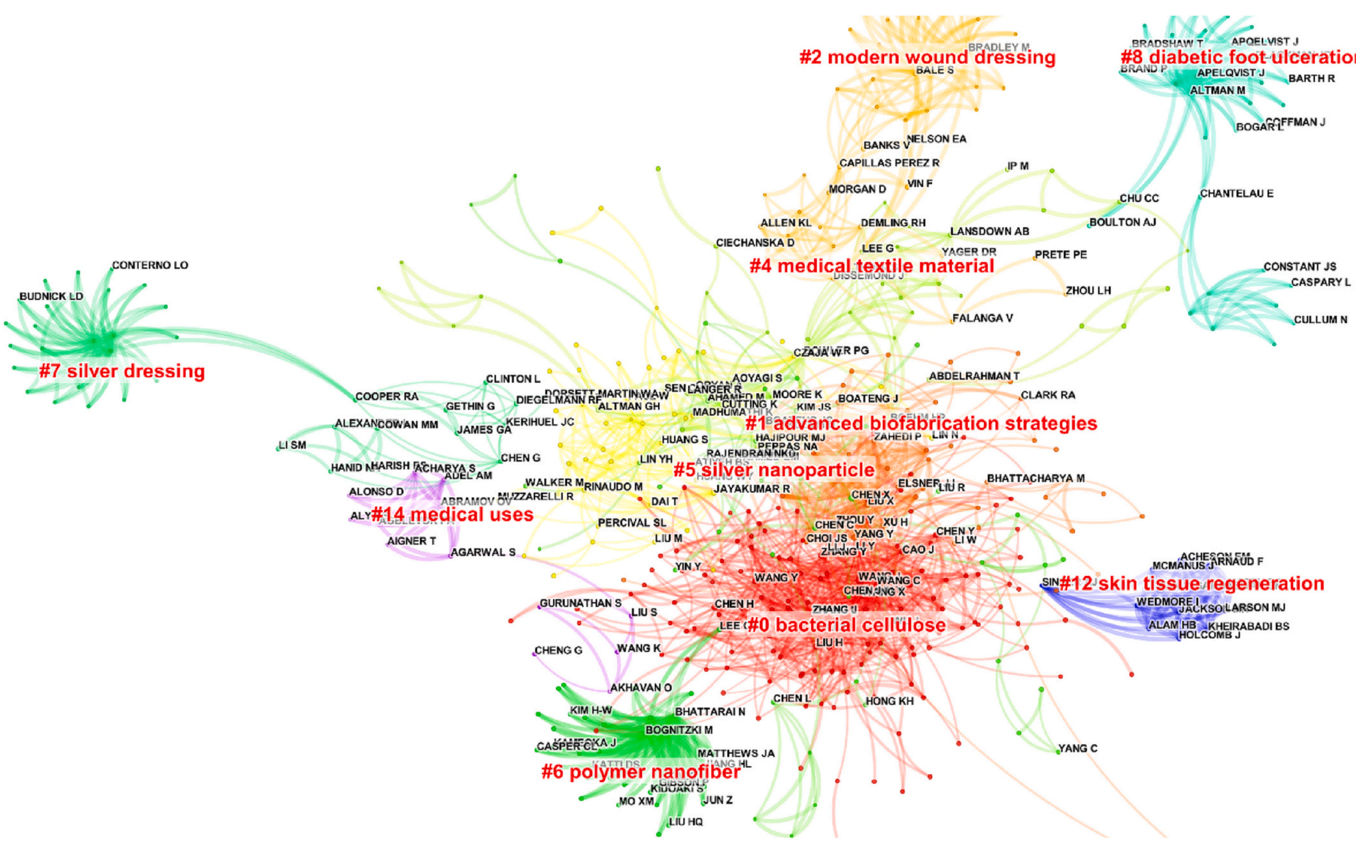

Fig. 2. Clusters labelled with subject category and the leading authors working on activated carbon mediated dressings.

cluster, Maneerung et al. (2008) reported that silver nanoparticle-infused bacterial cellulose shows antibacterial efficiency of 99.7 % whereas Lin et al. (2013) proposed chitosan-embedded bacterial cellulose as a potential candidate for wound dressing which showed antibacterial efficiency of 99.9 % compared to pristine bacterial cellulose (49.2 %). Osmokrovic et al. (2018) showed that Ca-alginate hydrogels composite containing activated carbon particles with adsorbed protein povidone iodine exhibited the capability to release the antimicrobial agents in physiological environment, thereby facilitating the wound healing process. On the other hand, the study carried out by Bhadauriya et al. (2018) revealed that immobilization of yeast with Cu nanoparticle-immersed carbon nanofibers resulted in a facile and highly efficient dressing material for diabetic wounds. Similarly, more research is being carried out to fabricate new innovative AC-based dressing involving efficient membrane-incorporated antibacterial agents (Tsai et al., 2014; Lin et al., 2016). More focus has to be involved in understanding the effect of AC dressing on skin tissue regeneration, utilization of different polymers, and incorporation of nanomaterials to enhance the dressing efficiency. These are emerging research that have to be explored further whereas previous works were limited to determining the efficiency of AC dressing in malodor adsorption and wound healing.

3.3. Analysis of keywords in AC-based wound dressing research

The evolution of keywords introduced by authors in representing their research findings on the development of AC dressing has been given in Fig. 3. These keywords could be used to understand the research progress associated with components of AC dressing. The appearance of keywords like "chronic disease", "debridement", and "antibiotic agent" in early period states that the initial research involved the determining the potential of using incorporated AC for treating chronic wounds as an antibacterial agent (Hampton, 2001; Park and Jang, 2003), debridement of wound tissues. The comparative efficiency of incorporating AC with other dressing materials to reduce wound area has been carried out by various studies (Kerihuel, 2010; Thomas and McCubbin, 2003). The incorporation of activated carbon with different antimicrobials like silver (Lin et al., 2012), alginate (Lee et al., 2007), and chitosan (Céline et al., 2013) increased its effectiveness in wound healing and also initiated the trials for modern wound dressing materials. Different case studies explaining the significance of AC dressing have also been reported (Tsai et al., 2014; Murphy, 2016). Advanced fabrication technologies have been adopted for improving the deodorant, antibacterial activity and no side effects of AC dressing (Gliścińska et al., 2012; Kim et al., 2018). The later appearance of "biocompatible", "tissue regeneration" in mid of 2010 indicates the research growth to examine the compatibility of AC dressing for cell proliferation and healing of wounds. The appearance of "cytotoxicity", "cell viability" indicates the ability of using AC as a dressing that induces no cytotoxic effects for growth of cells after dressing on the wound site. Multifunctional wound dressing containing AC helps in skin regeneration for accelerated wound closure (Lin et al., 2016; Bhadauriya et al., 2018 and Kaviyashri et al., 2021). The top 15 keywords possessing higher burst values have been given in Fig. 4. It can be observed that the keywords "activated carbon", "alginic acid", and "chronic disease" have the highest burst values which indicate that the respective keywords have been cited repeatedly during the highlighted time period. As stated earlier, owing to initial research exploration of strategies of employing AC for treating chronic wounds, these keywords appeared with higher burst values. The synergistic combination of silver and copper nanoparticles incorporated on AC showed antibacterial activity against *E. coli* and is proposed to use as a disinfectant (Biswas and Bandyopadhyaya, 2017). Nevertheless, keywords such as "tissue engineering" and "nanocomposite" currently exhibit relatively lower burst value, indicating a shifting focus towards emerging research on the synthesis of innovative dressings and the assessment of their potential using diverse tissue engineering techniques.

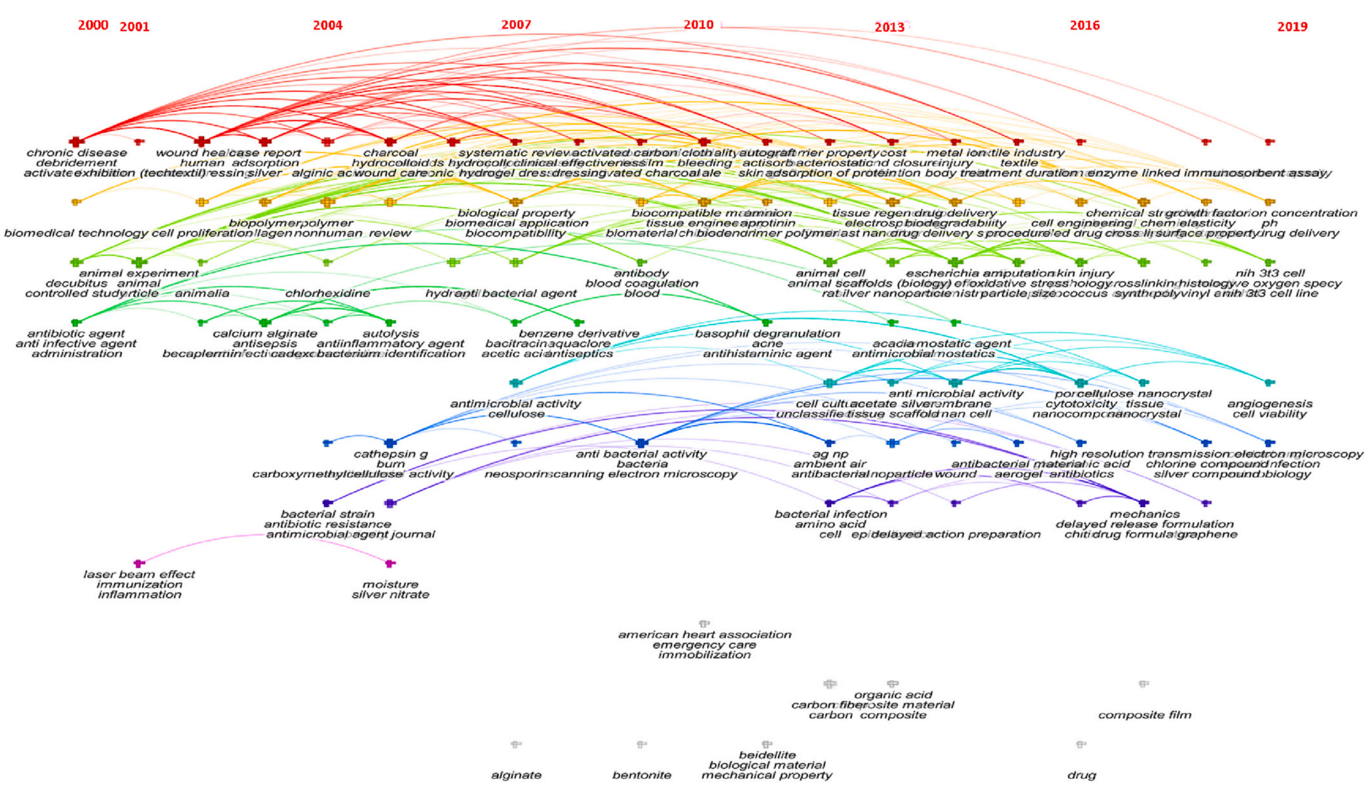

Fig. 3. Timeline of keywords applied to represent the scientific documents published on activated carbon mediated dressing.

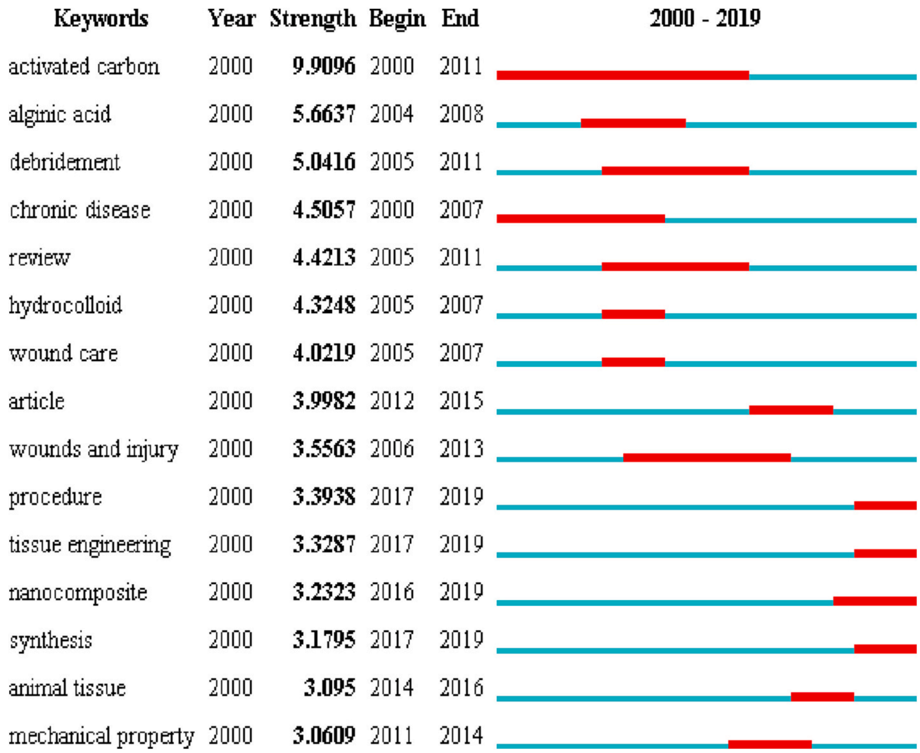

Fig. 4. List of top 15 keywords based on the burst strength in AC mediated wound healing research.

4. Features of activated carbon as a wound dressing material

4.1. Methods of production of activated carbon

The common carbon precursors for the preparation of AC include agricultural waste biomass, lignite, peat, anthracite, and bones (Tadda et al., 2016; Nwankwo et al., 2018). The activated carbon is being prepared through thermochemical conversion and activation of above-mentioned precursors (Chauhan et al., 2023). Techniques like pyrolysis (thermal decomposition of biomass under oxygen-limited conditions), gasification (degradation of feedstock at high temperature with steam or CO_2 as gasifying agent), hydrothermal carbonization (low-temperature carbonization with water as reaction medium) employing a suitable range of temperature, heating rate, pressure and residence time are used for the production of carbonaceous matter (Menya et al., 2020; Lan et al., 2023). Following the carbonization, activation of carbonaceous material can be carried out using either physical or chemical activating agents. The activation step could be processed either simultaneously during the carbonization of biomass or as a separate process after carbonization using physical or chemical activating agents. Physical activation of biomass involves higher temperatures from 800 °C to 1100 °C and the use of gases like steam, carbon dioxide, oxygen for activation (Yek et al., 2020). The impregnation of dehydrating chemicals like potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), and phosphoric acid (H_3PO_4) was used for chemical activation of organic biomass heated at a temperature ranging between 400 °C to 900 °C (Villota et al., 2019). Singh et al. (2017) compared the effectiveness of single-step activation with two-step activation using KOH and reported that surface area and microporous volume were less than those obtained from single-step activation. These techniques can be used to tailor the texture of activated carbon by regulating the carbonization reaction parameters and are aimed to produce AC to be used effectively in diverse applications.

4.2. Textural characteristics of activated carbon as adsorbent

Physical and chemical activation techniques are employed for improving the textural properties like pore enlargement and surface area to facilitate better adsorption (Kumar et al., 2022). Although physical activation is often considered eco-friendly and results in distinguished pore enlargement, it ensues an increased economic burden on account of its high power consumption. Chemical activation by alkali has been projected to improve the adsorptive capacity of carbonaceous materials for gas adsorption (Singh et al., 2017; Ahmed et al., 2019; Rehman et al., 2021). The gas adsorption efficiency of the activated carbon is determined by activation stages either through a single or two-step process (Rashidi and Yusup, 2017; Gomez-Delgado et al., 2022). (Altintig et al., 2016) produced activated carbon from corn cob using 85 % phosphoric acid with a ratio of 1:2 (corn cob: phosphoric acid) and then carbonized in a steel tubular reactor to be used as an antibacterial agent. The developed carbonaceous structures can be categorized further based on pore widths as microporous (<2 nm), mesoporous (between 2 nm–50 nm), and macroporous (>50 nm) (Ilomuanya et al., 2017; Chen and He, 2023). The existing pores are enhanced and the new pores are being formed at higher temperatures and these provide active sites for the adsorbates (Maneerung et al., 2016). AC produced at higher temperatures has a lower yield but improved textural characteristics than that produced at a lower temperature. The activated carbon produced at low temperatures contains low ash content and shows a positive effect on the adsorption capacity attributing to easier accession of the active pores. The percentage of carbon content, surface area, number of pores, and the corresponding pore volume encompass the influential characteristics of the AC determining its potential in adsorption (Bergna et al., 2018). The specific surface area, dispersion of pore density and other physicochemical properties are based on the process variables involved in the activation method.

4.3. Potential benefits of AC in biomedical applications

Activated carbon has been widely used as an effective adsorbent for various organic compounds owing to its higher surface area, sorption capacity, and chemical resistance (Maneerung et al., 2016; Wang et al., 2018). Owing to its adsorption behavior, it is being used for filtering biochemicals like interleukins in the blood (Huang et al., 2012; Zhu et al., 2023). The KOH-activated carbon with the increased surface area has been utilized for malodor adsorption and showed higher gas adsorption efficiency (Singh et al., 2017; Ahmed et al., 2019). The increased surface area on account of activation and carbonization increases the utilization efficiency of AC-based dressings for the removal of repulsive odor (Mikhalovsky et al., 2012; Tripathi et al., 2018). The valuable necessity of AC as a better adsorbent in the medical field is displayed in Fig. 5. The electrostatic interactions between the activated carbon surface and the protein molecule facilitate its adsorption at a pH lower than the isoelectric point. At pH above the isoelectric point, hydrophobic interactions take forward the adsorption of protein onto the surface of activated carbon (Vuorte et al., 2023). The activated carbon treated with 85 % phosphoric acid possesses a surface area of 970.38 m^2g^{-1} and showed an effective antibacterial effect against *Escherichia coli* (Altintig et al., 2016). The synergistic effect of activated carbon, silver nanoparticle and titanium dioxide in a composite showed better antibacterial activity compared to streptomycin (Parvathi et al., 2020). It has been reported that activated char can remove the endo and exotoxins from fluid in an *in vitro* study (Kerihuel, 2010). Activated carbon cloth (ACC) for medical applications was developed by the Chemical Defence Establishment, Port Down by pyrolysis of cellulose fabric like viscose rayon or acetate followed by heating for activation at specific conditions for the pore development. The ACC can be applied directly to the wound and is considered one of the safe practices of wound administration (Murphy, 2016; Scheer et al., 2017). These findings are imperative enough and emphasize the utilization of AC as a wound dressing material to fasten the wound healing process.

5. Fabrication and characterization of AC dressing material

5.1. Direct utilization of activated carbon cloth

AC derived from a natural source and used as a contact wound dressing without any chemical agent has been commercialized in the name of *Zorflex® VB-K*. The cloth is entirely made of 100 % AC and possessed inherent antimicrobial properties by entrapping the microorganism through van der Waals force of attraction and subsequently killing the pathogens (Chemviron Carbon, 2015). This cost-effective treatment expedited the healing of wounds within 2 weeks and reduced the associated pain and malodor of colonized and infected wounds by changing to a moist conducive environment for healing process (Madadian et al., 2023). It is cheap, safer with reduced bioburden and no adverse effects than other dressings (Murphy, 2016; Scheer et al., 2017).

5.2. Activated carbon-based dressings

Activated carbon finds application as wound interfacing layer, offering coverage for the wound and used in the form of either powder, particle, fibers, or their combinations. Its unique properties allow for immobilization, or attachment or containment between sealed layers of non-activated carbon-based cloth (Lavocah et al., 2019). The activated carbon inherently possesses antimicrobial activity and the adsorption of malodor, but the mesoporous structure of activated carbon is not capable enough for immobilizing the microorganisms durably leading to lesser bacteriostatic activity. In order to maintain improved contamination control and adsorption of odor and wound exudates, secondary layers are being added to wound care dressings. Most of the research involved in the use of AC or its based dressings employed commercial products from the market or brought from other research laboratories leading to limited lab-based studies associated with the production of AC or its dressings (Ashfaq et al., 2017; Osmokrovic et al., 2018). Gliścińska et al. (2012) used a nonwoven AC cloth, which was prepared by pyrolysis of viscose at 500 °C and activated at 800 °C for an hour. Dibutyrylchitin (DBC) fibers were deposited by electrospinning method onto the cloth to adsorb wound exudates for hastening tissue growth and the material was impregnated with an antimicrobial agent (Microcide-N750). The AC/DBC cloth has enhanced sorption, non-allergenic, noncytotoxic nature, and cidal effects to yeast, fungi, and bacteria compared to commercial silver-infused AC dressing. A small difference in the percentage was noted in the fibrinogen concentration of the AC/DBC dressing and established that these materials could also be introduced as potential wound healing agents in further experimentation. (Lin et al., 2016) designed the inner layer of activated carbon with gentamicin to prevent bacterial infection and the outer layer with gelatin/chitosan/epigallocatechin gallate nanoparticle incorporated in a γ- PGA/gelatin hydrogel to prevent inflammation and facilitate reepithelization and wound healing. Incorporating activated carbon dressings with silver (Ag) to harness its antiseptic and antimicrobial properties becomes a promising approach in combating bacteria that exhibit multi-resistance against various antibiotics. In these embodiments, the activated carbon fiber (ACF) or cloth is immersed in silver acetate/nitrate solution in the presence of heat leading to the reduction of silver and deposited on the surface of AC. These embodiments show a uniform distribution of silver particles on the activated carbon and increase the surface area. These composites have the ability to reduce the colony-forming units of different bacterial strains causing less damage to fibroblast cells (Lin et al., 2012; Lavocah et al., 2019).

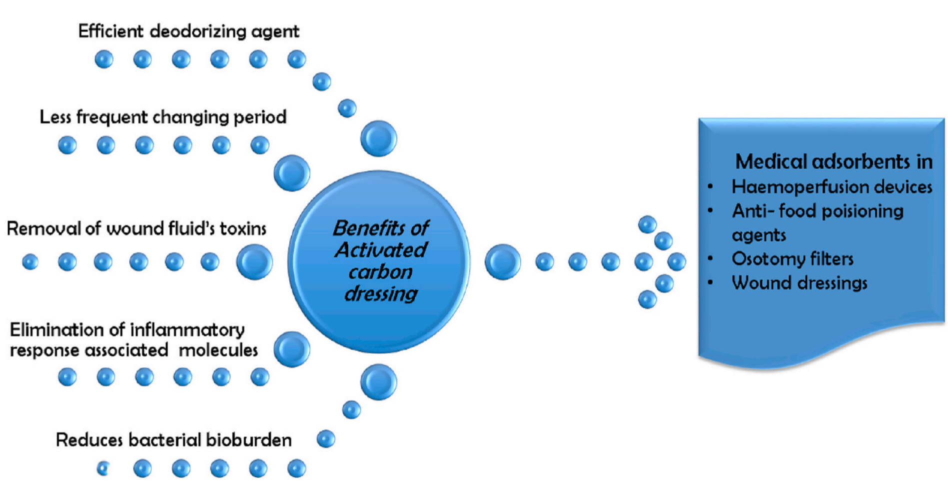

Fig. 5. Specific features of activated carbon dressing for biomedical applications.

5.3. Incorporation of nanomaterials in AC dressings

Despite advancements in diagnostics and antibiotics, bacterial resistance leads to the requirement for a higher dose of antibiotics and causes side effects. Hence, antimicrobial nanomaterials incorporated with AC have been used which controls infection without provoking bacterial resistance (Mirhaj et al., 2022). Cu and Zn nanoparticle dispersed activated carbon nanofiber has been synthesized through the chemical vapor deposition method with acetylene as a carbon source. A significant reduction in the surface area has been observed after impregnation owing to the blockage of pores by metal salts and the surface contained suitable functional groups for bacterial adhesion (Ashfaq et al., 2016). The composite containing activated carbon powder and silver nanoparticles was fabricated under heat treatment where 10 % of silver particles were reduced and got incorporated into the porous structure of AC. These composites showed excellent deodorant and antibacterial activity than pure AC (Kim et al., 2018). Zn^{2+} has been used to enhance the wound healing process since it is a co-factor for enzyme systems that take part in wound repair. The AC composite containing zinc oxide nanoparticles showed higher antibacterial activity to gram-positive bacteria than gram-negative bacteria and no side effects like local skin inflammation or itchiness were observed (Sharifuddin et al., 2019).

The chemical impregnation and subsequent calcination are being used for the incorporation of metal nanocrystalline or its associated nanoparticles in AC dressing (Ashfaq et al., 2016; Kim et al., 2018). The

Table 1
List of a few patents involving carbonaceous material for wound healing.

Patent number	Dressing composition	Description	References
US20120064145A1	A bi-layered wound dressing consisting of: • Upper layer: Made of polymer (either one or combination among gelatin, hyaluronic acid, collagen, polyglutamic acid, chitosan, fucoidan, and sodium alginate) with added anti-infective antibiotics (macrolides, tetracyclines) or Chinese herb medicine (shenjiyu-honggao paste extract) • Bottom layer: Activated carbon cloth layer loaded with skin-related epithelial cells	• The antibiotics provided defencee against the bacteria located outside the surroundings, thus averting the injury from additional infection. • Activated carbon cloth layer loaded with epithelial cells afforded the growth and attracted the neighbouring healthy cells forming aggregation followed by collagen release for the advancement in the wound healing mechanism.	Lin and Yeh (2012)
US9510977B2	The wound dressing consisted of • One or more absorbing layers made of a foamed polymer (polyurethane resin, polyvinyl ester resin, ethylene vinyl acetate resin) consisting of a huge number of pores • A large multitude of stretched polyacrylonitrile based ACFs distributed into all the absorbing layers and partly projected into the pores.	• The ACF dimensions ranged in microns. • The absorbing layer absorbed the exudate dripping from the wound to avoid the wound from the saturation of the fluid • The fibers inside the absorbing member emitted far-infrared rays for facilitating blood circulation surrounding the wound for rapid restoration of the wound.	Ko et al. (2016)
US20160361478A1	The wound dressing comprised of: • A cover and • A wound dressing pad that encompassed a foam pad (granufoam possessing a urethane base) and an antimicrobial substrate (a nylon fiber coated with silver) provided at the wound side of the foam pad. • An activated carbon layer existed between the foam pad and antimicrobial substrate.	• Application in negative pressure wound therapy. • Cover aided in the protection of the dressing pad. • The dressing pad was designed for placement over a wound site with the antimicrobial substrate between the foam pad and the wound site.	Eddy (2016)
US20170100504A1	The wound dressing layers comprised of: • The first and second layer each independently comprising of one or mixture of nylon, polyvinylidene fluoride (PVDF) or polytetrafluoroethylene (PTFE), ethylene methyl acrylate (EMA), polyvinyl chloride, polyvinyl dichloride, polyurea, polyolefin, ethylene vinyl acetate copolymer, polyethylene, polypropylene, polyesters, polyethylene terephthalate fabric with, middle activated carbon layer.	• Different incorporations of dressings could be prepared using the materials. • Either the first or the second layer could be used as a hydrophobic film or as a layer pervious to air and fluid circulation through the dressing and contact the wound • An adhesive layer could be included that permitted the wound dressing to attach itself to the tissues surrounding the wound.	Taylor and Lavocah (2017)
US9782512B2	A multi-layered dressing consisted of: • One or more layers of hydrocolloid developed from a collagen foam of porcine, bovine or equine origin, and • A layer of spherical activated carbon placed between layers. • Additionally, the presence of one or more therapeutic substances selected from the group of antimicrobial, disinfecting, inflammation-inhibiting, and wound healing-promoting substances.	• The layer comprising hydrocolloid was designed for facing the wound to be treated. • The activated carbon cloth possessed micropores in the angstrom range for adsorptive properties and produced biocidal/static properties to foreign pathogens.	Von Blücher et al. (2017)
US10045885B2	The wound dressing material composed of: • a substrate (activated carbon cloth) and • bicarbonate in the ratio of 2.5:8 with a film-forming agent. • The film-forming agent and the bicarbonate was present in the ratio of 1:2 with respect to each other.	• The substrate adsorbed blood or extra bodily fluid toxins discharged from a wound. • The film-forming agent was used for maximizing the attachment of the bicarbonate to the substrate.	Coffey and Verduzco (2018)
US20200155355A1	The wound dressing consisted of: • a superabsorbent layer made of hydrophilic polyurethane foam • back-up hydrophobic coating, and • activated carbon layer comprised of silver antimicrobial was placed between the superabsorbent layer and the backing layer.	• The superabsorbent layer was constructed for the absorption of wound fluid. • The backing layer was extensively impervious to liquid and penetrable to vapor. • The activated carbon layer was designed for increased moisture vapor transmission rate of the wound dressing.	Hill et al. (2020)
US10596545B2	• Web kind filamented precursor material for the ACF produced from polyacrylonitrile material • Developed by arranging and beating those precursor filaments.	• The ACF fabric was manufactured by activating the filament for: • increased durability and • enriched crystallinity of yarns forming the precursor fabric	Lee et al. (2020)

nanocomposites are then characterized using analytical instruments to understand the surface characteristics and antimicrobial activity to evaluate their capability for utilization as dressing material. Owing to the deposition of nanocrystalline or nanoparticle substrate, a reduction in porosity occurs relative to their original AC fabric. Studies have also proved that the adsorptive capacities of AC-infused nanocrystalline/nanoparticle materials were relatively better than that of original AC fabric due to existing multiple functional groups on its surface which has a complex-forming tendency. A significant decrease in the bacterial burden was also observed in AC-infused nanocrystalline/nanoparticle substrates compared to that of original AC as an effect of the metallic ion discharge in the extermination of the bacterial membrane integrity (Kim et al., 2018; Ji et al., 2020). To avoid adverse effects due to metal impregnations, hydrocolloid-based dressings are being invented. The hydrocolloid layer consisting of collagen acts as a wound healing promoter. The hydrocolloid layer preferably constitutes 20 % to 60 % of the total thickness of the dressing and shows a synergistic effect with activated carbon (Von Blücher et al., 2017). A few patents have been listed in Table 1 stating the composition and description of AC dressings in the field of wound care.

6. Classification of AC dressings

Wound dressings are classified into different types based on various aspects.

- ➢ Primary, secondary dressing, and multilayer dressing (based on composition)
- ➢ Passive, interactive, and bioactive dressings (based on the nature of their action)
- ➢ Absorbent and non-absorbent dressing (based on the absorption capacity for wound exudates).

The schematic classification of wound dressing has been described in Fig. 6 illustrating the different types of dressing based on various distinguishing factors.

6.1. Classification based on dressing composition

Primary dressings are the type of dressing that are immediately utilized on the wound exterior while a secondary dressing is applied to the upper position of the primary dressing. Secondary dressings are mainly used for additional absorption of wound exudates or fortification of dressing in place (Wu et al., 2020). The type of dressings that consist of many layers for effective adsorption of odor and wound discharge were termed multi-layered dressings. These dressings usually comprise a multi-layered absorbent wound contact region, a hydrophobic coating zone made of the same or different fabric, and AC cloth to retain wound fluid. A recent study by Scheer et al. (2017) suggested that the usage of 100 % AC cloth called *Zorflex* manufactured by Chemviron Carbon, a European operating group under Calgon Carbon Corporation could be used single-handedly for healing the ulcerated wounds compared to the other dressings owing to its cost-effectiveness. The cloth was initially introduced in *Actisorb* dressing during the 1970s (previously under Systagenix wound management later acquired jointly by 3 M Healthcare and KCl Acelity company) and later in other multicomponent dressings as an odor adsorbing textile. The cloth owing to its microporosity after activation harnessed swift adsorption kinetics leading to its usage in various applications other than dressings which included ostomy filters, chemical, biological and nuclear warfare in the military, and other filtration/catalyst purposes in industries (Turaga et al., 2012). It could also be exercised as a primary dressing owing to its antimicrobial action without the incorporation of chemicals, the conductive features in tissue granulation, modulation of the protease, and the odor levels. Its conductive behavior was referred to as poor electrostatic forces termed Van der Waals forces (which served in the enrichment of blood flow around the area and enhanced wound closing rates) leading to binding of bacteria and other wound-degraded by-products (Houghton, 2017). Murphy (2016) projected the beneficial outcome in the usage of *Zorflex* compared to other antimicrobial-infused dressings by reduction of infection and decreased wound exudates within a month. A recent study by Sharifuddin et al. (2019) presented the utilization of *Zorflex*-activated cloth and reported no side effects like skin irritation. Table 2 illustrates a few commercialized AC wound dressings, as instances of the aforementioned classification. These dressings were used in the treatment of fungating carcinomas, lesions and tumours, ulcerative, diabetic, palliative, all kinds of malodorous, post-surgical, first and second-degree burn wounds, necrotic pressure sores, lacerations, and faecal fistulae (Mikhalovsky et al., 2012; Powers et al., 2016).

6.2. Classification based on interaction with the wound

Passive dressings are applied directly on the wound acting as a cover, over the wound. Interactive dressing includes polymeric forms and films, acting as a barrier for bacteria and aims to reduce the wound odor and exudates. Bioactive dressings contain biological molecules like

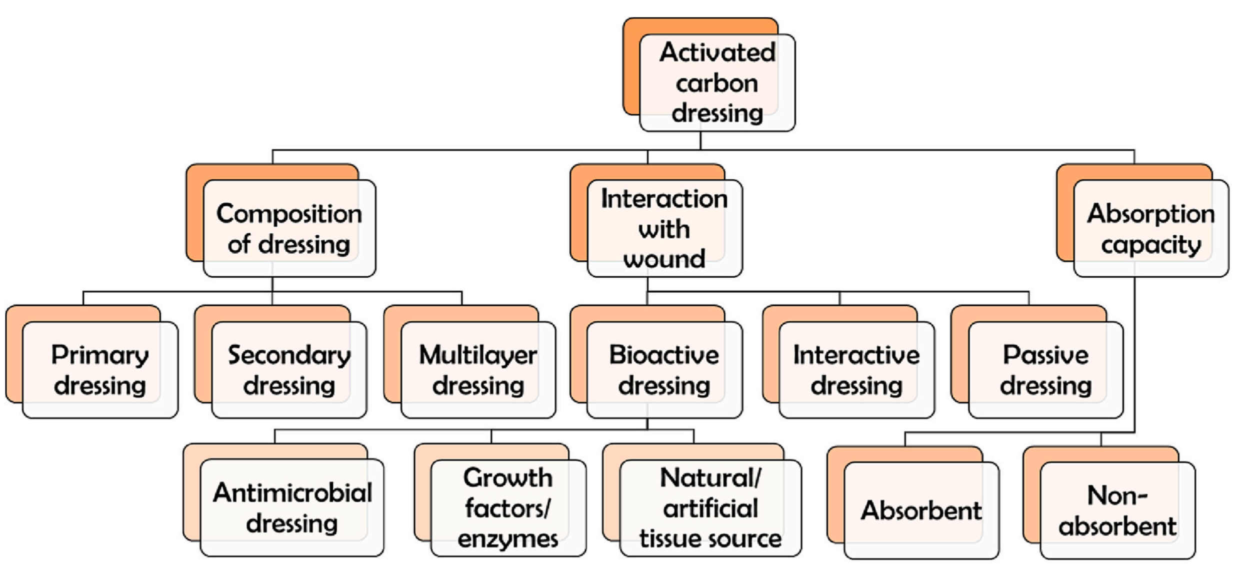

Fig. 6. Classification of activated carbon dressings based on different factors.

Table 2
Description of few activated carbon dressings sold for commercial use.

Name of dressing	Dressing Composition	Contraindications	Manufacturing company	Trademark	References
Actisorb® (currently not in use)	A primary dressing that consisted of an ACC infiltrated with silver placed in a nonwoven spun sleeve of nylon material.	Not presented for third degree burns and could not be applied to patient sensitive to silver	3 M Healthcare +KCl, an Acelity company	3M KCI United by purpose.	Qin (2015)
Actisorb® plus 25	A primary dressing that consisted of an ACC composed of 95–98 % carbon derived from woven viscose rayon textile with an infusion of 0.15 % silver. The cloth was enclosed in a porous sleeve made of nylon material.			KCI AN ACELITY COMPANY	Qin (2015)
Actisorb® Silver 220	A primary dressing that consisted of an ACC, infiltrated with silver placed inside a spun nylon covering. The name of the dressing arose due to the infusion of 220 mg silver per 100 g ACC.				Qin (2015)
Clinisorb®	A multi-layered dressing that consisted of ACC fitted between the layers of viscose with a coating of polyamide as its outer cover.	Could not be applied on dry wounds	CliniMed Ltd	CliniMed®	Qin (2015)
Sorbsan Plus Carbon	A multi-layered activated carbon dressing with calcium alginate as the wound interacting layer aided by another adsorbent layer.	Must not be practiced on wounds with low exudate or necrotic tissue else might get adhered to wound surface.	Aspen medical Ltd	Aspen Medical	Qin (2015)
Pharmpad Carbon®	A triple layered haemostatic dressing composed of activated carbon layer inserted in between the layers of viscose or nylon "thermal bond" nonwoven.	• It could not be applied to patients with a known allergy to alginates. • It should not be applied to dry or necrotic tissues.	Pharmaplast Ltd	Pharmaplast	Qin (2015), McQueen (2011)
Pharmapad Carbon Silver®	A slim haemostatic dressing that consisted of an activated charcoal layer and wound communication layer covered with polyethylene net holding silver.	• Not intended to be used as a surgical sponge or to achieve haemostasis in heavily bleeding wounds.			Pharmapad Carbon Silver® (2020)
Pharma Algi® F Ag Carbon	A haemostatic dressing that consisted of a thin carbon felt placed in between the two non-woven layers made of 100 % calcium alginate fibers and silver for malodour adsorption.				Pharma Algi® F Carbon (2020)
Pharma superFoam® Carbon	The dressing comprised of five-layered design, made of activated carbon pad, fitted between two layers of polyurethane foam. Top polyurethane foam layer subsequently was coated with porous polyurethane film, while the corresponding lower polyurethane foam layer was coated with permeable polyurethane film. Activated charcoal layer was utilized for the adsorption of offensive odours associated with chronic wounds. External and internal polyurethane foam layers managed moderate to heavy wound exudates. Semi-permeable farthest polyurethane film coating acted as a barrier against viruses and bacteria. The films were water-resistant too but permitted vaporisation of excess wound discharge absorbed by the foam, thereby increasing the total fluid handling capacity (TFHC) of the whole entity. The pervious polyurethane film wound interacting layer was non-adherent, allowed easy removal of dressing without distress. Sealed edges prohibited lateral leakage in case of heavily exuding wounds which in turn prevented soaking of normal skin adjoining the wound.	The dressing • Should not be applied to dry wounds and necrotic tissues. • Should not be utilized on wounds that prolonged till bones or muscle location. • Should not be applied with oxidizing agents such as hypochlorite or hydrogen peroxide solutions as they possessed the potential to breakdown the absorbent hydrocolloid entity of the dressing.			PharmasuperFoam® Product Range (2020)
CarboFLEX®	The dressing composed of five layers (bottom to top) which consisted of: First outer gel layer was a wound interacting layer made up of both alginate and carboxymethyl cellulose fibers. The innermost second layer	Recognized sensitiveness to the components in the dressing	ConvaTec Ltd	ConvaTec	Qin (2015); Joshi and Purwar (2019)

(*continued on next page*)

Table 2 (*continued*)

Name of dressing	Dressing Composition	Contraindications	Manufacturing company	Trademark	References
	made up of ethylene methyl acrylate (EMA) film maintained hydrophobic valves in the range of microns assisted in unilateral movement and detainment of the wound discharge to the carbon layer. It also aided in the increased shelf life of ACC. Third middle layer consisted of ACC for odor adsorption. The layer above the activated carbon being the fourth layer was a nonwoven absorbent pad whose role was to retain excess wound discharge and the outer fifth layer was also an EMA film layer.				
CARBONET®	The dressing composed of a less adherent wound interaction layer made of knitted viscose supported by an absorbent layer made of cellulose fibers to which the former was attached to a layer of ACC fitted between either sides of polythene net.		Smith and Nephew, Inc.		Qin (2015)
Kaltocarb® (currently not in use)	An alginate dressing that composed of an ACC inserted between the absorbent wound interacting layer made up of calcium alginate fibers and a corresponding outer layer made of polyester viscose.	Less significant if utilized on wounds that are dry or covered with hard black necrotic tissue.	BritCair Company	Not available	Qin (2015), Voncina et al. (2016)
Lyofoam® C	A multicomponent dressing made of Polyurethane deliquescent foam layers placed on either side of the cloth consisting of activated carbon granules and a corresponding polyurethane foam water repellent layer covered the inner hydrophilic layers.	It would be of convenience if not applied to dry wounds or hard black necrotic tissue until they were surgically removed or by some other means.	Mölnlycke Healthcare		Qin (2015)
KoCarbonAg Antimicrobial dressing	The dressing was mainly composed of a wound contact layer made of polyethylene terephthalate (PET) to absorb wound fluid, centre layer consisted of ACC and an outer low adherent layer made of polythene membrane for reduction of pain while changing the dressing.	• The dressing should not be used with oil-based medicinal liquids. • Not suitable for patients allergic to activated carbon and silver.	Biomedical Carbon Technology Co., Ltd.		Tsai et al. (2014)
Askina® Carbosorb	An elastic wound dressing composed of a dense, spongy layer made of viscose rayon non-woven, and a layer of activated carbon for adsorption of bacteria and its associated repulsive odor.	It possesses limited absorption capacity. As a result, it could be utilized solely on low wound discharging wounds, or in support with other water permeable dressings for /moderately to heavily discharging wounds and their corresponding malodour.	B. Braun Medical Ltd		Ashton et al. (2014)

proteoglycans, collagen, protein, and other biological metabolites to facilitate wound healing process (Davis and McLister, 2016). As mentioned previously in Section 5.1, the activated carbon cloth is non-occlusive and could be applied for wound healing directly as a passive dressing without the requirement of any drug. ACC impregnated with silver (*Actisorb Silver 220*) has been used as a primary dressing for diabetic foot ulcers to prevent the exuberant granulating tissue and odor reduction that hampers the healing process (Huang et al., 2012; Haycocks and Chadwick, 2014). The ACC prepared from viscose rayon irradiated with gamma radiation increased the external surface area and mesoporous structure (Sekulić et al., 2009). It also increased antioxidative activity of scavenging the free radicals and antibacterial properties which favours its application as a dressing material (Budimir, 2020). The direct application of AC as a dressing causes fouling and decreases the adsorption efficiency especially odor adsorbing tendency due to contamination with macromolecules from wound fluids.

Interactive dressing acts as a barrier for bacterial passage, thereby assisting the activated carbon in reducing the accumulation of fluid around the wound surface and also in the porous structure (Dhivya et al., 2015). The AC containing plasticized agarose films showed efficient malodor adsorption both in the liquid and vapor phases. The adsorption efficiency of AC has been preserved by encapsulation using agarose to prevent biofilm formation on the pores (Illsley et al., 2017). The odor from the wound is typically eliminated by the third dressing change, providing comfort to the patient. Semenič and Aleksovska (2019) reported that cellulose-based AC dressing can treat chronic ulcer wounds in which pain and odor got reduced within a month. Venous leg ulcer, pressure ulcer and necrotizing fasciitis are the type of wounds where interactive dressings are being prescribed (Egas et al., 2018).

Bioactive dressings are modern dressings which include biomaterials playing a vital role in the wound healing process. Generally, the bioactive dressing includes antimicrobials, growth factors, and nutritional sources like collagen, chitosan and alginates (Marrella et al., 2017; Ahmed et al., 2018). The bioactive, biocompatible and non-toxic nature of the dressing promotes cell growth and interactions facilitating the faster healing of wounds. Antibiotic agents were incorporated in multi-layered dressings using natural and biodegradable polymers like gelatin/chitosan for eliminating the bacteria. The AC-based scaffold enhances the fibroblast cell growth and migration to the wound site (Huang et al., 2012; Lin et al., 2016). The ACF impregnated with copper and yeast extract has been used for diabetic wound healing. The composite showed significant glucose consumption with simultaneous inhibition of bacterial infection and enhanced cell viability and proliferation (Bhadauriya et al., 2018). A significant amount of research has been reported on bioactive materials incorporating polymer-based chronic wound healing modalities (Dhivya et al., 2015; Wu et al., 2020).

6.3. Classification based on absorption capacity

Classification of dressing based on absorption capacity is divided into two types which include absorbent and non-absorbent dressing. Non-absorbent dressings involve primary or secondary dressings containing activated carbon cloth and an absorbent layer which is generally less absorptive. However, an additional layer for the absorption of wound exudates is required besides improving odor and bacterial bioburden reduction. These dressings are normally preferred for small wounds/burns with fewer exudates. Some of the examples include *Actisorb 220*, *Pharmapad Carbon*, *Askina Carbosorb*, *Carbopad VC*, and *Clinisorb* (McQueen, 2011; Illsley et al., 2017). Absorbent dressings usually consist of layers of fibrous textile or spongy foam-like layers held together with the AC and possessing great absorption capacity. Generally, these dressings comprise alginates, polyurethane foam, and fibers as the layer facing wound. On account of their porosity, they also generate a moist surrounding like that of a hydrogel which encourages the healing of wounds. The presence of an absorptive layer and adsorption of odor prevents the release of volatile organic compounds to the atmosphere. Some of the examples of these materials include *Carboflex*, *Pharma Algi F Carbon*, and *Sorbsan Plus Carbon* (McQueen, 2011; Rajendran and Anand, 2014).

7. Comparison of commercialized dressings with AC dressings

Chronic wound closure rates were achieved with much hard work only by overcoming various comorbidities associated with the wound itself. Even though several wound dressing agents exist globally, the need for relative comparison between the dressings is essential for getting insights into therapeutic efficacy and maximal cost-effectiveness. AC cloth (*Zorflex*®) itself solely delivers better antimicrobial traits, adsorption of malodor, and is less luxurious compared to the conventional gauze, betadine ointments, foam dressings, alginate dressings and Negative Wound Pressure Therapy (NPWT) (Scheer et al., 2017). A comparative study was performed on the varying quantities of silver-infused in ACF with commercialized dressings *Sorbalgon*® (made of calcium alginate) and *SilverIon*® (made of a polyamide textile coated with silver) by Lin et al. (2012). Through *in vitro* testing, the results indicated that the silver-infused ACF dressings exhibited lower cytotoxicity towards fibroblast cells. Furthermore, *in vivo* experimentation demonstrated that these dressings promoted higher tissue granulation rates in individuals with *Pseudomonas aeruginosa*-infected wounds compared to other dressings available in the market. The silver-containing AC unveiled a remarkable antibacterial effect, biocompatibility, non-cytotoxicity, and growth of tissues compared to commercial silver dressings (Lin et al., 2014). Another study by Lin et al. (2016) compared the different commercialized silver dressings such as Acticoat®7 (comprised of a silver-coated polythene mesh placed between both layers of rayon), Aquacel®Ag (comprised of dressing made of Hydrofiber™ technology with aided ionic silver), KoCarbonAg® (comprised of an AC layer placed between polyethylene terephthalate (PET) and polythene membrane) and a traditional gauze dressing to check their effectiveness in reducing the bacterial burden with enhanced epithelialization rates. KoCarbonAg® silver dressing was not only found to be very effective in reducing bacterial colonization in inflammation phase but also stimulate collagen synthesis in the subsequent proliferation phase among all the dressings. A randomized control trial was carried out to compare the polyacrylate wound dressing containing an AC layer to that of a standard hydro cellular foam dressing consisting of silver. The cost associated with hard-to-heal wounds is higher and the evaluation of wound dressings that aid in the reduction of wound size and fasten wound healing is essential for the affected individuals and also for medical practitioners (Probst et al., 2019).

8. Alternate advancements in the production of dressings

One of the essential requirements in the development of chronic wound dressing involves the prevention of bacterial multiplication as they concurrently influence the poor degree of healing wounds (Powers et al., 2013). Therefore, advancements in dressings that exhibit antimicrobial action for effective bactericidal potential were invented.

Silver is distinguished as an ancient antimicrobial agent that is stable in metallic conditions rather than in aqueous solutions due to the liberation of ions. When the ions from the silver-infused ACF dressings bind to bacterial DNA, they induce changes in the cell membrane, disrupt cellular respiration, hinder cell division, and interfere with enzyme function. These cumulative effects eventually result in bacterial death (Das et al., 2017). The incorporation of silver into AC dressings leveraged its unique characteristic to accomplish three important functions. Firstly, it effectively bound both bacteria and endotoxins released during cell lysis. Secondly, it efficiently trapped the odor molecules associated with bacterial activity. Lastly, the antimicrobial properties of silver contributed to the eradication of bacteria and their associated endotoxins (White, 2013). A study conducted by (Lin et al., 2016) that evaluated the efficacy of silver-infused AC dressings, thereby proposing that the dressings prohibited bacterial multiplication in wounds by hindering the entrance of bacteria from outside and held the bacteria inside the dressing and the bacterial burden was decreased and hastened the healing of wounds. Its mechanism of action on wounds has been represented comprehensively in Fig. 7 based on the studies of Murphy (2016) and Joshi and Purwar (2019). Reduction of ulcers and increased closure rates of the wound were found using silver-infused AC dressings (Kerihuel, 2010). Silver compounds earlier in the form of silver nitrates, silver sulfadiazine were also used in the preparation of ointments for burn wounds (Gupta et al., 2017). Many bacteria in the progression of time grew resistance to silver by either detoxification in the cytoplasm or decreased intake due to its intracellular molecular mechanisms (Boateng and Catanzano, 2020). Few patients on the other hand might be susceptible to silver. Such dressings could not be employed in those situations consequently. Necessity might arise as a result of the usage of silver-infused dressings with only the adsorption of bacteria and other toxins without discharge of silver ions (Percival et al., 2019). Even though strong proof exists for the size reduction of wounds, thereby is a deficiency in data for complete recovery of wound healing and its corresponding degree of healing. Silver-infused dressings had shown significant activity for a lesser span but for extended period effects, with vague details (Carter et al., 2010; Itani and Iblasi, 2019).

It has been reported that utilization of silver dressings showed higher risk for adverse effects since it penetrates the cell membrane. And, it is also suspected to be involved in Alzheimer's and Parkinson's disease by damaging the insulator proteins and surrounding nerves (Von Blücher et al., 2017). To avert this issue, other metallic nanoparticles with antimicrobial properties were investigated. Zinc (Zn) nanoparticles are commonly used for their antimicrobial properties and also for their antioxidant potential in wound dressings (Ahmed et al., 2018). Since Zn is an essential compound needed for collagen and protein synthesis by translation of certain DNA elements in DNA metalloproteins, production of antibodies and cell proliferation, it aids in the process of wound healing (Ashfaq et al., 2016; Sharifuddin et al., 2019). The biocompatibility and less toxic nature emphasize its utilization as a suitable candidate in biomedical applications. In the study conducted by Osmokrovic et al. (2019), the authors employed zinc-alginate beads containing 20 % w/w activated carbon (AC) and 0.5 % w/w sodium alginate. These beads were immersed in a solution of 1.8 % w/w zinc nitrate hexahydrate. The results revealed that 60 % of the initial AC quantity was released within five days when exposed to a physiological saline solution. Furthermore, the presence of Zn^{2+} effectively eliminated

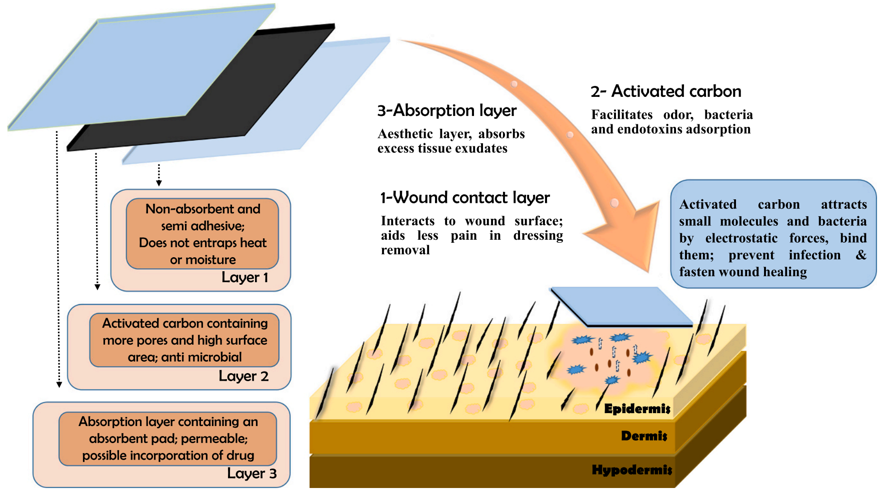

Fig. 7. A typical activated carbon dressing and its mechanism in wound healing.

the bacteria present in the suspension.

Copper (Cu) plays a significant role in endothelial growth, stabilizing the proteins in skin, cross-linking of collagens and angiogenesis, and accelerating the wound closure. It causes cell death through membrane disruption, inhibition of protein synthesis and biochemical pathways (Bhadauriya et al., 2018). The asymmetrically distributed Cu and Zn nanoparticles on the surface of ACF got released at different rates activating the platelet aggregation, increasing the proliferation of macrophages and enhancing haemostasis due to higher protein adsorption ability of the metal composite containing ACF (Ashfaq et al., 2017). The combination of Cu and Zn is being used as a potential antibacterial agent owing to an impressive contribution to wound healing process by enhancing the cell-mediated reactions.

Wound dressings play a crucial role in various therapies such as Negative Pressure Wound Therapy (NPWT) and post-surgery treatments. In these cases, the dressings serve as canisters to collect wound exudates. While silver-infused dressings have limitations, multi-layered dressings were introduced to address these issues. However, it is important to note that the use of multi-layered dressings can impose additional financial burdens on individuals. Hence there aroused the need for the development of cost-effective potential dressings. Biocompatible macro and microporous layers are being used in dressing material to restrict the entry of larger pathogens, fungal spores, pollen and detoxify the wound through size exclusion and ion barrier provided with an absorbent and AC in layers (Karthikeyan and Karthikeyan, 2019). In conjunction with an absorbent pad, moisture can be regulated more efficiently than AC being used alone. Polymer-based carbonaceous adsorbent is more effective than AC and acid-treated AC in removing the toxins and other biomolecules. It is being used with immobilised enzymes for biomedical applications. These methods aid in controlled release of AC in treating wounds and the release rate is based on the concentration of polymer and activated carbon (Osmokrovic et al., 2018; Sultan et al., 2019). AC-coated polyurethane and polyethylene mesh were used as substrates and as defensive layers for the potential antibacterial activity of nanofibers prepared by electrospinning method (Allafchian et al., 2018). The combination of AC nanomaterial with antibacterial drugs/material and bioactive or non-active polymer will increase the therapeutic effect and comfortability. The comprehensive growth of research in fields like material science, nanomaterial engineering, membrane technology, and tissue engineering in recent years is evident from Fig. 2. New innovative dressings could be fabricated which function as physical and chemical barriers, and also facilitate easier cell delivery approach and antibacterial barrier (Liu et al., 2020).

9. Research gaps and future perspectives

As observed by comprehensive analysis, the following aspects have to be considered to improve the currently available technologies for AC dressing-mediated wound healing.

- ➢ A combination of advanced therapeutic dressings is essential to overcome the challenges associated with single dressing material and treatment procedures addressing the problems in chronic wound healing.
- ➢ Novel combination of carbon materials can be used for the improvement of AC fabric for regulated healing of wounds.
- ➢ The absorption capabilities should be developed by magnifying its scope in utilization with other therapeutic and medical possibilities without limiting its facilities to dressings.
- ➢ *In vivo* studies involving AC dressings and metal nanoparticles have to be conducted for different wounds for the determination of wound closure rate, histocompatibility and prolonged release of metal nanoparticles for effective antibacterial activity.
- ➢ The existence of limitations in different AC dressings due to clinical studies conducted for a limited period would be inevitable and could be enhanced by long-term experimentations.
- ➢ Skilled and knowledgeable medical professionals with expertise in conducting case studies are essential.
- ➢ Randomized controlled trials as well as the active participation of individuals with the regulation of essential variables to be tested in a defined period are anticipated.
- ➢ There is a need to enhance additional research and conduct optimized trials in wound care, following approved ethical permissions. This will contribute to the improvement of patient's quality of life and overall well-being.

10. Conclusion

This article provides an overall idea of developing AC and its based dressings for wound care. The review also presented their inevitability in chronic wounds and stated the various types of commercialized AC dressings with their composition. Scientometric analysis revealed that the utilization of AC dressings so far in the medical field was intended for better administration of malodorous wounds with additional antibacterial protection. It was observed that China is the leading nation in this research arena however the collaboration network between other countries has to be enhanced significantly. The research has evolved from using AC for adsorption of wound malodor to studying the interaction between the AC and bacteria, biocompatibility studies, advanced bio fabrication techniques in order to produce multi-layered dressings. However, some research gaps have been encountered during the scientometric analysis where lack of long-term clinical trials, *in vivo* studies, mechanisms associated with cellular interaction and associated changes have to be explored further. The future scope of using AC as a dressing material should focus on combination of advanced therapeutic dressings with carbon materials. *In vivo* studies explaining the beneficial interactive effects of AC with cells for skin regeneration in different wounds has be explored. Techno-economic assessment of AC-based dressing material facilitates the analysing the feasibility and potential bottlenecks of the research for producing cost-effective products. Overall, the scientometric study of AC for wound dressing provided an overview of the state of the art of current trends and deficiencies in the research of AC dressing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Abbas, M., Uckay, I., Lipsky, B.A., 2015. In diabetic foot infections antibiotics are to treat infection, not to heal wounds. Expert. Opin. Pharmacother. 16 (6), 821–832. https://doi.org/10.1517/14656566.2015.1021780.

Ahmed, R., Tariq, M., Ali, I., Asghar, R., Khanam, P.N., Augustine, R., Hasan, A., 2018. Novel electrospun chitosan/polyvinyl alcohol/zinc oxide nanofibrous mats with antibacterial and antioxidant properties for diabetic wound healing. Int. J. Biol. Macromol. 120, 385–393. https://doi.org/10.1016/j.ijbiomac.2018.08.057.

Ahmed, M.B., Johir, M.A.H., Zhou, J.L., Ngo, H.H., Nghiem, L.D., Richardson, C., Moni, M.A., Bryant, M.R., 2019. Activated carbon preparation from biomass feedstock: clean production and carbon dioxide adsorption. J. Clean. Prod. 225, 405–413. https://doi.org/10.1016/j.jclepro.2019.03.342.

Akhmetova, A., Saliev, T., Allan, I.U., Illsley, M.J., Nurgozhin, T., Mikhalovsky, S., 2016. A comprehensive review of topical odor-controlling treatment options for chronic wounds. J. Wound Ostomy Cont. Nurs. 43 (6), 598–609. https://doi.org/10.1097/WON.0000000000000273.

Allafchian, A., Jalali, S.A.H., Kabirzadeh, N., 2018. Characterization and investigation of antibacterial properties of nylon 66/TPS/Ag NPs nanofibers. Micro Nano Lett. 13 (12), 1747–1751. https://doi.org/10.1049/mnl.2018.5142.

Altintig, E., Arabaci, G., Altundag, H., 2016. Preparation and characterization of the antibacterial efficiency of silver loaded activated carbon from corncobs. Surf. Coat. Technol. 304, 63–67.

Ashfaq, M., Verma, N., Khan, S., 2016. Copper/zinc bimetal nanoparticles-dispersed carbon nanofibers: a novel potential antibiotic material. Mater. Sci. Eng. C. 59, 938–947. https://doi.org/10.1016/j.msec.2015.10.079.

Ashfaq, M., Verma, N., Khan, S., 2017. Highly effective Cu/Zn-carbon micro/nanofiber-polymer nanocomposite-based wound dressing biomaterial against the P. aeruginosa multi-and extensively drug-resistant strains. Mater. Sci. Eng: C. 77, 630–641. https://doi.org/10.1016/j.msec.2017.03.187.

Ashton, R., Leppard, B., Leppard, B., 2014. Differential Diagnosis in Dermatology, 4th ed. CRC Press. https://doi.org/10.1201/b21273.

Bacakova, L., Pajorova, J., Tomkova, M., Matejka, R., Broz, A., Stepanovska, J., Prazak, S., Skogberg, A., Siljander, S., Kallio, P., 2020. Applications of nanocellulose/nanocarbon composites: Focus on biotechnology and medicine. Nanomaterials 10 (2), 196. https://doi.org/10.3390/nano10020196.

Behera, B., Selvam, S.M., Paramasivan, B., 2022a. Research trends and market opportunities of microalgal biorefinery technologies from circular bioeconomy perspectives. Bioresour. Technol. 351, 127038 https://doi.org/10.1016/j.biortech.2022.127038.

Behera, B., Selvam, S.M., Balasubramanian, P., 2022b. Hydrothermal processing of microalgal biomass: circular bio-economy perspectives for addressing food-water-energy nexus. Bioresour. Technol. 359, 127443 https://doi.org/10.1016/j.biortech.2022.127443.

Bergna, D., Varila, T., Romar, H., Lassi, U., 2018. Comparison of the properties of activated carbons produced in one-stage and two-stage processes. J. Carbon Res. 4 (3), 41. https://doi.org/10.3390/c4030041.

Bhadauriya, P., Mamtani, H., Ashfaq, M., Raghav, A., Teotia, A.K., Kumar, A., Verma, N., 2018. Synthesis of yeast-immobilized and copper nanoparticle-dispersed carbon nanofiber-based diabetic wound dressing material: simultaneous control of glucose and bacterial infections. ACS Appl. Bio. Mater. 1 (2), 246–258. https://doi.org/10.1021/acsabm.8b00018.

Bhardwaj, N., Kundu, S.C., 2010. Electrospinning: a fascinating fiber fabrication technique. Biotechnol. Adv. 28 (3), 325–347. https://doi.org/10.1016/j.biotechadv.2010.01.004.

Biswas, P., Bandyopadhyaya, R., 2017. Synergistic antibacterial activity of a combination of silver and copper nanoparticle impregnated activated carbon for water disinfection. Environ. Sci. Nano 4 (12), 2405–2417.

Boateng, J., Catanzano, O., 2020. Silver and silver nanoparticle-based antimicrobial dressings. In: Boateng, J. (Ed.), Therapeutic Dressings and Wound Healing Applications. John Wiley and Sons, pp. 157–184. https://doi.org/10.1002/9781119433316.ch8.

Budimir, M.D., 2020. Modification of Carbon Nanocomposites by Electromagnetic Irradiation for Biomedical Application. Micro and nanotechnologies/Microelectronics. Université de Lille; Univerzitet u Beogradu.

Canchy, L., Kerob, D., Demessant, A.L., Amici, J.M., 2023. Wound healing and microbiome, an unexpected relationship. J. Eur. Acad. Dermatol. Venereol. 37, 7–15. https://doi.org/10.1111/jdv.18854.

Carter, M.J., Tingley-Kelley, K., Warriner III, R.A., 2010. Silver treatments and silver-impregnated dressings for the healing of leg wounds and ulcers: a systematic review and meta-analysis. J. Am. Acad. Dermatol. 63 (4), 668–679. https://doi.org/10.1016/j.jaad.2009.09.007.

Céline, P.B., Antoine, V., Denis, B., Laurent, V., Laurent, D., Catherine, F., 2013. Development and characterization of composite chitosan/active carbon hydrogels for a medical application. J. Appl. Polym. Sci. 128 (5), 2945–2953. https://doi.org/10.1002/app.38414.

Chauhan, P.R., Raveesh, G., Pal, K., Goyal, R., Tyagi, S.K., 2023. Production of biomass derived highly porous activated carbon: a solution towards in-situ burning of crop residues in India. Bioresour. Technol. Rep. 22, 101425 https://doi.org/10.1016/j.biteb.2023.101425.

Chemviron Carbon, 2015. Clinical Focus: Zorflex® VB-K Antimicrobial Wound Dressings. Chemviron Carbon, Houghton le Spring.

Chen, C., 2006. CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature. J. Am. Soc. Info. Sci. Technol. 57 (3), 359–377. https://doi.org/10.1002/asi.20317.

Chen, Z., He, R., 2023. Competitive adsorption characteristics of gasoline evaporated VOCs in microporous activated carbon by molecular simulation. J. Mol. Graphics Modell. 121, 108444 https://doi.org/10.1016/j.jmgm.2023.108444.

Coffey, M., Verduzco, R., 2018. U.S. Patent Application No. 15/970,152.

Corbett, B.E., Blank, N.R., Markova, A., 2020. Comprehensive wound care for malignant wounds. In: Alavi, A., Maibach, H.I. (Eds.), Local Wound Care for Dermatologists, 1. Springer Cham, pp. 163–175. https://doi.org/10.1007/978-3-030-28872-3_17.

da Costa Santos, C.M., de Mattos Pimenta, C.A., Nobre, M.R.C., 2010. A systematic review of topical treatments to control the odor of malignant fungating wounds. J. Pain Symptom Manag. 39 (6), 1065–1076. https://doi.org/10.1016/j.jpainsymman.2009.11.319.

Das, B., Dash, S.K., Mandal, D., Ghosh, T., Chattopadhyay, S., Tripathy, S., Roy, S., 2017. Green synthesized silver nanoparticles destroy multidrug resistant bacteria via reactive oxygen species mediated membrane damage. Arab. J. Chem. 10 (6), 862–876. https://doi.org/10.1016/j.arabjc.2015.08.008.

Davis, J., McLister, A., 2016. Passive and interactive dressing materials. In: Davis, J. (Ed.), Smart Bandage Technologies: Design and Application, 1. Elsevier, pp. 93–144.

Dhivya, S., Padma, V.V., Santhini, E., 2015. Wound dressings-a review. BioMed 5 (4), 22. https://doi.org/10.7603/s40681-015-0022-9.

Eddy, P.E., 2016. U.S. Patent Application No. 15/179,346.

Egas, L.S., de Carvalho Reis, E.N.R., da Silva, L.F., Bonardi, J.P., de Lima, V.N., Ferreira, P.H.S.G., de Deus, C.B.D., Júnior, I.R.G., 2018. Cervicofacial necrotizing fasciitis and drugs. J. Craniofac. Surg. 29 (6), 617–618. https://doi.org/10.1097/SCS.0000000000004679.

Flanagan, M., 2013. Wound Healing and Skin Integrity: Principles and Practice, First ed. John Wiley and Sons, United Kingdom.

Forss, J.R., Tolhurst, B.A., Bowyer, C.J., Brooks, E.L., Allan, I.U., 2022. The properties of an activated carbon-containing agarose film for the amelioration of 2-amino acetophenone malodour as produced in chronic wounds infected with Pseudomonas aeruginosa. J. Mater. Sci. 57 (34), 16460–16470.

Gliścińska, E., Babeł, K., Krucińska, I., Kowalczyk, E., 2012. Activated carbon/dibutyrylchitin (dbc) as fibrous antibacterial noncytotoxic wound dressing material. Fibres Text. East. Eur 20 (2), 91.

Gomez-Delgado, E., Nunell, G., Cukierman, A.L., Bonelli, P., 2022. Agroindustrial waste conversion into ultramicroporous activated carbons for greenhouse gases adsorption-based processes. Bioresour. Technol. Rep. 18, 101008 https://doi.org/10.1016/j.biteb.2022.101008.

Gupta, S., Kumar, N., Tiwari, V.K., 2017. Silver sulfadiazine versus sustained-release silver dressings in the treatment of burns: a surprising result. Indian J. Burns 25 (1), 38. https://doi.org/10.4103/ijb.ijb_22_17.

Hampton, S., 2001. Actisorb Silver 220: a unique antibacterial dressing. Br. J. Community Nurs. 6 (Sup1), 17–19. https://doi.org/10.12968/bjcn.2001.6.Sup1.5254.
Hampton, S., 2015. Managing biofilm by using dressings. Br. J. Commuity Nurs. 20, S10–S12. https://doi.org/10.12968/bjcn.2015.20.Sup6.S10.
Han, G., Ceilley, R., 2017. Chronic wound healing: a review of current management and treatments. Adv. Ther. 34 (3), 599–610. https://doi.org/10.1007/s12325-017-0478-y.
Haycocks, S., Chadwick, P., 2014. Using an activated charcoal dressing with silver for malodour, infection and overgranulation in diabetic foot ulcers. Diabetic Foot J. 17 (2), 74.
Hill, C.R., Poole, L.J., Bolton, R.E., 2020. U.S. Patent Application No. 16/619,606.
Houghton, P.E., 2017. Electrical stimulation therapy to promote healing of chronic wounds: a review of reviews. Chronic Wound Care Manag. Res. 4, 25–44. https://doi.org/10.2147/CWCMR.S101323.
Huang, W.Y., Yeh, C.L., Lin, J.H., Yang, J.S., Ko, T.H., Lin, Y.H., 2012. Development of fibroblast culture in three-dimensional ACF-based scaffold for wound healing. J. Mater. Sci. Mater. Med. 23 (6), 1465–1478. https://doi.org/10.1007/s10856-012-4608-4.
Hunt, A.M.A., Gibson, J.A., Larrivee, C.L., O'Reilly, S., Navitskaya, S., Busik, J.V., Waters, C.M., 2017. Come to the light side: in vivo monitoring of pseudomonas aeruginosa biofilm infections in chronic wounds in a diabetic hairless murine model. J. Vis. Exp. 128, e55991 https://doi.org/10.3791/55991.
Illsley, M.J., Akhmetova, A., Bowyer, C., Nurgozhin, T., Mikhalovsky, S.V., Farrer, J., Allan, I.U., 2017. Activated carbon-plasticised agarose composite films for the adsorption of thiol as a model of wound malodour. J. Mater. Sci. Mater. Med. 28 (10), 154. https://doi.org/10.1007/s10856-017-5964-x.
Ilomuanya, M.O., Nashiru, B., Ifudu, N.D., Igwilo, C.I., 2017. Effect of pore size and morphology of activated charcoal prepared from midribs of *Elaeis guineensis* on adsorption of poisons using metronidazole and Escherichia coli O157: H7 as a case study. J. Microsc. Ultrastruct. 5 (1), 32–38. https://doi.org/10.1016/j.jmau.2016.05.001.
Itani, H., Iblasi, A., 2019. The controversial and diverse conclusions of clinical studies on the use of silver in the management of patients with venous leg ulcers. Wounds 6 (1), 18–23.
Ji, T.H., Fan, P.D., Zhang, A.R., Tian, Y.Q., 2020. Excellent adsorptive behaviors of ZnO nanoparticle-deposited activated carbon covered with nano-graphene oxide. J. Nanosci. Nanotechnol. 20 (4), 2436–2441. https://doi.org/10.1166/jnn.2020.17195.
Joshi, M., Purwar, R., 2019. Composite dressings for wound care. In: Rajendran, S. (Ed.), Advanced Textiles for Wound Care, 2. Woodhead Publishing, pp. 313–327.
Karthikeyan, A., Karthikeyan, A., 2019. U.S. Patent No. 10,463,760. U.S. Patent and Trademark Office, Washington, DC.
Kaviyashri, Y., Selvam, S.M., Arunachalam, T., Paramasivan, B., 2021. Potential of keratin loaded activated carbon and aqueous extracts of *Allium sativum* for the development of antibacterial wound dressing. Mater. Today: Proc. 47, 321–325. https://doi.org/10.1016/j.matpr.2021.04.486.
Kerihuel, J.C., 2010. Effect of activated charcoal dressings on healing outcomes of chronic wounds. J. Wound Care 19 (5), 208–214. https://doi.org/10.12968/jowc.2010.19.5.48047.
Kim, M.H., Cho, D., Kwon, O.H., Park, W.H., 2018. Thermal fabrication and characterization of Ag nanoparticle-activated carbon composites for functional wound-dressing additives. J. Alloys Compd. 735, 2670–2674. https://doi.org/10.1016/j.jallcom.2017.11.347.
Ko, T.H., Lin, J.H., Pei-Hsun, C.H.O.U., Su, Y.J., 2016. U.S. Patent No. 9,510,977. U.S. Patent and Trademark Office, Washington, DC.
Krishnamoorthy, N., Pathy, A., Kapoor, A., Paramasivan, B., 2023. Exploring the evolution, trends and scope of microalgal biochar through scientometrics. Algal Res. 69, 102944 https://doi.org/10.1016/j.algal.2022.102944.
Kumar, D.P., Ramesh, D., Subramanian, P., Karthikeyan, S., Surendrakumar, A., 2022. Activated carbon production from coconut leaflets through chemical activation: Process optimization using Taguchi approach. Bioresour. Technol. Rep. 19, 101155 https://doi.org/10.1016/j.biteb.2022.101155.
Lan, J., Wang, B., Bo, C., Gong, B., Ou, J., 2023. Progress on fabrication and application of activated carbon sphere in recent decade. J. Ind. Eng. Chem. 120, 47–72. https://doi.org/10.1016/j.jiec.2022.12.045.
Lavocah, W., Curtis, P., Brown, R., Sleigh, D., 2019. U.S. Patent Application No. 16/472,637.
Leaper, D., Assadian, O., Edmiston, C.E., 2015. Approach to chronic wound infections. Br. J. Dermatol. 173 (2), 351–358. https://doi.org/10.1111/bjd.13677.
Lee, G., Anand, S.C., Rajendran, S., Walker, I., 2007. Efficacy of commercial dressings in managing malodorous wounds. Br. J. Nurs. 16 (Sup1), S14–S20. https://doi.org/10.12968/bjon.2007.16.Sup1.27086.
Lee, T.S., Cho, E.J., Yoon, J.Y., 2020. U.S. Patent No. 10,596,545. U.S. Patent and Trademark Office, Washington, DC.
Liao, C., Li, Y., Tjong, S.C., 2019. Bactericidal and cytotoxic properties of silver nanoparticles. Int. J. Mol. Sci. 20 (2), 449. https://doi.org/10.3390/ijms20020449.
Lin, Y.S., Yeh, C.L., 2012. U.S. Patent Application No. 13/015,301.
Lin, Y.H., Lin, J.H., Li, T.S., Wang, S.H., Yao, C.H., Chung, W.Y., Ko, T.H., 2016. Dressing with epigallocatechin gallate nanoparticles for wound regeneration. Wound Repair and Regeneration 24 (2), 287–301.
Lin, Y.H., Lin, J.H., Wang, S.H., Ko, T.H., Tseng, G.C., 2012. Evaluation of silver-containing activated carbon fiber for wound healing study: in vitro and in vivo. J Biomed Mater Res B Appl Biomater 100 (8), 2288–2296. https://doi.org/10.1002/jbm.b.32800.
Lin, W.C., Lien, C.C., Yeh, H.J., Yu, C.M., Hsu, S.H., 2013. Bacterial cellulose and bacterial cellulose–chitosan membranes for wound dressing applications. Carbohydr. Polym. 94 (1), 603–611. https://doi.org/10.1016/j.carbpol.2013.01.076.
Lin, Y.H., Hsu, W.S., Chung, W.Y., Ko, T.H., Lin, J.H., 2014. Evaluation of various silver-containing dressing on infected excision wound healing study. J. Mater. Sci. Mater. Med. 25 (5), 1375–1386. https://doi.org/10.1007/s10856-014-5152-1.
Lin, Y.H., Hsu, W.S., Chung, W.Y., Ko, T.H., Lin, J.H., 2016. Silver-based wound dressings reduce bacterial burden and promote wound healing. Int. Wound J. 13 (4), 505–511. https://doi.org/10.1111/iwj.12467.
Liu, Y., Li, Q.Q., Zhang, H., Yu, S.P., Zhang, L., Yang, Y.Z., 2020. Research progress on the use of micro/nano carbon materials for antibacterial dressings. New Carbon Mater. 35 (4), 323–335. https://doi.org/10.1016/S1872-5805(20)60492-9.
Madadian, E., Naseri, E., Legault, R., Ahmadi, A., 2023. Development of 3D-printable albumin–alginate foam for wound dressing applications. 3D Print Addit. Manuf. https://doi.org/10.1089/3dp.2022.0241.
Maneerung, T., Tokura, S., Rujiravanit, R., 2008. Impregnation of silver nanoparticles into bacterial cellulose for antimicrobial wound dressing. Carbohydr. Polym. 72 (1), 43–51. https://doi.org/10.1016/j.carbpol.2007.07.025.
Maneerung, T., Liew, J., Dai, Y., Kawi, S., Chong, C., Wang, C.H., 2016. Activated carbon derived from carbon residue from biomass gasification and its application for dye adsorption: Kinetics, isotherms and thermodynamic studies. Bioresour. Technol. 200, 350–359. https://doi.org/10.1016/j.biortech.2015.10.047.
Marrella, A., Lagazzo, A., Barberis, F., Catelani, T., Quarto, R., Scaglione, S., 2017. Enhanced mechanical performances and bioactivity of cell laden-graphene oxide/alginate hydrogels open new scenario for articular tissue engineering applications. Carbon 115, 608–616. https://doi.org/10.1016/j.carbon.2017.01.037.
McQueen, R.H., 2011. Odour control of medical textiles. In: Bartels, V.T. (Ed.), Handbook of Medical Textiles. Woodhead Publishing, pp. 387–416.
Melotto, G., Tunprasert, T., Forss, J.R., 2022. The effects of electrical stimulation on diabetic ulcers of foot and lower limb: a systematic review. Int. Wound J. 19 (7), 1911–1933. https://doi.org/10.1111/iwj.13762.
Menya, E., Olupot, P.W., Storz, H., Lubwama, M., Kiros, Y., John, M.J., 2020. Optimization of pyrolysis conditions for char production from rice husks and its characterization as a precursor for production of activated carbon. Biomass Convers. Biorefin. 10 (1), 57–72. https://doi.org/10.1007/s13399-019-00399-0.
Mikhalovsky, S., Sandeman, S., Howell, C., Phillips, G., Nikolaev, V.G., 2012. Biomedical applications of carbon adsorbents. In: Tascon, J.M.D. (Ed.), Novel Carbon Adsorbents. Elsevier, pp. 639–669. https://doi.org/10.1016/B978-0-08-097744-7.00021-1.
Minsart, M., Mignon, A., Arslan, A., Allan, I.U., Van Vlierberghe, Dubruel, P., 2021. Activated carbon containing PEG-based hydrogels as novel candidate dressings for the treatment of malodorous wounds. Macromol. Mater. Eng. 306 (1), 2000529.
Mirhaj, M., Labbaf, S., Tavakoli, M., Seifalian, A.M., 2022. Emerging treatment strategies in wound care. Int. Wound J. 19 (7), 1934–1954. https://doi.org/10.1111/iwj.13786.
Morrison, K.D., Martin, K.A., Wimpenny, J.B., Loots, G.G., 2022. Synthetic antibacterial minerals: harnessing a natural geochemical reaction to combat antibiotic resistance. Sci. Rep. 12 (1), 1–11. https://doi.org/10.1038/s41598-022-05303-x.
Muller, B.R., 2021. Preparation and characterization of K_2CO_3-doped powdered activated carbon for effective in-vitro adsorption of deoxynivalenol. Bioresour. Technol. Rep. 15, 100703 https://doi.org/10.1016/j.biteb.2021.100703.
Murphy, N., 2016. Reducing infection in chronic leg ulcers with an activated carbon cloth dressing. Br. J. Nurs. 25 (12), S38–S44.
Nageshwari, K., Balasubramanian, P., 2022. Evolution of struvite research and the way forward in resource recovery of phosphates through scientometric analysis. J. Clean. Prod. 357, 131737 https://doi.org/10.1016/j.jclepro.2022.131737.
Nikolaev, V.G., Samsonov, V.A., 2014. Analysis of medical use of carbon adsorbents in China and additional possibilities in this field achieved in Ukraine. Artif. Cells Nanomed. Biotechnol. 42 (1), 1–5. https://doi.org/10.3109/21691401.2013.856017.
Nwankwo, I.H., Nwaiwu, N.E., Nwabanne, J.T., 2018. Production and characterization of activated carbon from animal bone. Am. J. Eng. Res. 7 (7), 335–341.
Oopath, S.V., Baji, A., Abtahi, M., Luu, T.Q., Vasilev, K., Truong, V.K., 2023. Nature-inspired biomimetic surfaces for controlling bacterial attachment and biofilm development. Adv. Mater. Inter. 10 (4), 2201425 https://doi.org/10.1002/admi.202201425.
Osmokrovic, A., Jancic, I., Vunduk, J., Petrovic, P., Milenkovic, M., Obradovic, B., 2018. Achieving high antimicrobial activity: Composite alginate hydrogel beads releasing activated charcoal with an immobilized active agent. Carbohydr. Polym. 196, 279–288. https://doi.org/10.1016/j.carbpol.2018.05.045.
Osmokrovic, A., Jančić, I., Janković-Castvan, I., Petrović, P., Milenković, M., Obradović, B., 2019. Novel composite zinc-alginate hydrogels with activated charcoal aimed for potential applications in multifunctional primary wound dressings. Hem. Ind. 73 (1), 37–46. https://doi.org/10.2298/HEMIND180629003O.
Park, S.J., Jang, Y.S., 2003. Preparation and characterization of activated carbon fibers supported with silver metal for antibacterial behavior. J. Colloid Interface Sci. 261 (2), 238–243. https://doi.org/10.1016/S0021-9797(03)00083-3.
Park, E., Long, S.A., Seth, A.K., Geringer, M., Xu, W., Chavez-Munoz, C., Mustoe, T.A., 2016. The use of desiccation to treat Staphylococcus aureus biofilm-infected wounds. Wound Repair Regen. 24 (2), 394–401. https://doi.org/10.1111/wrr.12379.
Parvathi, V.P., Umadevi, M., Sasikala, R., Parimaladevi, R., Ragavendran, V., Mayandi, J., Sathe, G.V., 2020. Novel silver nanoparticles/activated carbon co-doped titania nanoparticles for enhanced antibacterial activity. Mater. Lett. 258, 126775 https://doi.org/10.1016/j.matlet.2019.126775.

Pathy, A., Ray, J., Paramasivan, B., 2020. Biochar amendments and its impact on soil biota for sustainable agriculture. Biochar 2, 287–305. https://doi.org/10.1007/s42773-020-00063-1.
Pathy, A., Ray, J., Paramasivan, B., 2021. Challenges and opportunities of nutrient recovery from human urine using biochar for fertilizer applications. J. Clean. Prod. 304, 127019 https://doi.org/10.1016/j.jclepro.2021.127019.
Percival, S.L., Salisbury, A.M., Chen, R., 2019. Silver, biofilms and wounds: resistance revisited. Crit. Rev. Microbiol. 45 (2), 223–237. https://doi.org/10.1080/1040841X.2019.1573803.
Perikleous, E.P., Gkentzi, D., Bertzouanis, A., Paraskakis, E., Sovtic, A., Fouzas, S., 2023. Antibiotic resistance in patients with cystic fibrosis: past, present, and future. Antibiotics 12 (2), 217. https://doi.org/10.3390/antibiotics12020217.
Pharma-Algi® F Ag Dressings, 2020. Pharmaplast. https://pdf.medicalexpo.com/pdf/pharmaplast/pharma-algi-f-ag/69684-183176.html accessed on 10.07.
Pharmapad Carbon Silver®, 2020. Pharmaplast. https://pdf.medicalexpo.com/pdf/pharmaplast/pharmapad-carbon-silver/69684-183113.html accessed on 10.07.
PharmasuperFoam® Product Range, 2020. Pharmaplast. https://pdf.medicalexpo.com/pdf/pharmaplast/pharmasuperfoam/69684-183179.html accessed on 10.07.
Powers, J.G., Morton, L.M., Phillips, T.J., 2013. Dressings for chronic wounds. Dermatol. Ther. 26 (3), 197–206. https://doi.org/10.1111/dth.12055.
Powers, J.G., Higham, C., Broussard, K., Phillips, T.J., 2016. Wound healing and treating wounds: chronic wound care and management. J. Am. Acad. Dermatol. 74 (4), 607–625. https://doi.org/10.1016/j.jaad.2015.08.070.
Probst, S., Saini, C., Rosset, C., Skinner, M.B., 2022. Superabsorbent charcoal dressing versus silver foam dressing in wound area reduction: a randomised controlled trial. J. Wound Care 31 (2), 140–146.
Probst, S., Saini, C., Skinner, M.B., 2019. Comparison of sterile polyacrylate wound dressing with activated carbon cloth and a standard non-adhesive hydrocellular foam dressing with silver: a randomised controlled trial protocol. J. Wound Care 28 (11), 722–728. https://doi.org/10.12968/jowc.2019.28.11.722.
Qin, Y., 2015. Medical Textile Materials, first ed. Woodhead Publishing.
Rajendran, S., Anand, S.C., 2014. High performance textiles for wound care. In: Lawrence, C.A. (Ed.), High Performance Textiles and their Applications. Woodhead Publishing, pp. 190–222. https://doi.org/10.1533/9780857099075.190.
Rashidi, N.A., Yusup, S., 2017. Potential of palm kernel shell as activated carbon precursors through single stage activation technique for carbon dioxide adsorption. J. Clean. Prod. 168, 474–486. https://doi.org/10.1016/j.jclepro.2017.09.045.
Rehman, A., Heo, Y.J., Nazir, G., Park, S.J., 2021. Solvent-free, one-pot synthesis of nitrogen-tailored alkali-activated microporous carbons with an efficient CO_2 adsorption. Carbon 172, 71–82. https://doi.org/10.1016/j.carbon.2020.09.088.
Reinboldt-Jockenhöfer, F., Babadagi, Z., Hoppe, H.D., Risse, A., Rammos, C., Cyrek, A., Blome, C., Benson, S., Dissemond, J., 2021. Association of wound genesis on varying aspects of health-related quality of life in patients with different types of chronic wounds: results of a cross-sectional multicentre study. Int. Wound J. 18 (4), 432–439. https://doi.org/10.1111/iwj.13543.
Scheer, H.S., Kaiser, M., Zingg, U., 2017. Results of directly applied activated carbon cloth in chronic wounds: a preliminary study. J. Wound Care 26 (8), 476–481. https://doi.org/10.12968/jowc.2017.26.8.476.
Sekulić, D.R., Babić, B.M., Kljajević, L.M., Stašić, J.M., Kaluđerović, B.V., 2009. The effect of gamma radiation on the properties of activated carbon cloth. J. Serb. Chem. Soc. 74 (10), 1125–1132. https://doi.org/10.2298/JSC0910125S.
Semenič, D., Aleksovska, N., 2019. An atypical chronic ulcer caused by acute myeloid leukemia. Wounds 31 (4), E25–E28.
Sharifuddin, S.A.B., Ismail, S.B., Abdullah, I., Mohamad, I., Mohammed, J.S., 2019. Antibacterial evaluation of activated carbon cloth with Ag^+ impregnated with ZnO nanoparticles. Res. J. Text. Appar. 23 (3), 232–243. https://doi.org/10.1108/RJTA-09-2018-0056.
Sharma, G., Thakur, B., Naushad, M., Kumar, A., Stadler, F.J., Alfadul, S.M., Mola, G.T., 2018. Applications of nanocomposite hydrogels for biomedical engineering and environmental protection. Environ. Chem. Lett. 16 (1), 113–146. https://doi.org/10.1007/s10311-017-0671-x.
Singh, G., Kim, I.Y., Lakhi, K.S., Srivastava, P., Naidu, R., Vinu, A., 2017. Single step synthesis of activated bio-carbons with a high surface area and their excellent CO_2 adsorption capacity. Carbon 116, 448–455. https://doi.org/10.1016/j.carbon.2017.02.015.
Širić, I., Eid, E.M., Taher, M.A., El-Morsy, M.H., Osman, H.E., Kumar, P., Adelodun, B., Abou Fayssal, S., Mioč, B., Andabaka, Ž., Goala, M., 2022. Combined use of spent mushroom substrate biochar and PGPR improves growth, yield, and biochemical response of cauliflower (Brassica oleracea var. botrytis): a preliminary study on greenhouse cultivation. Horticulturae 8 (9), 830. https://doi.org/10.3390/horticulturae8090830.
Soonmin, H., Akram, M., Rashid, A., Laila, U., Zainab, R., 2022. Uses of activated carbon in medicine area: short review. EPRA Int. J. Res. Dev. 7 (7), 34–39.
Stucker, M., Moll, C., Rudolph, T., Robak-Pawelczyk, B., Jünger, M., Schultz-Ehrenburg, U., Altmeyer, P., 2003. Fibrinogen adsorption–a new treatment option for venous leg ulcers? VASA. Z. Gefasskrankheiten 32 (3), 173–177. https://doi.org/10.1024/0301-1526.32.3.173.
Sultan, M.T., Moon, B.M., Yang, J.W., Lee, O.J., Kim, S.H., Lee, J.S., Lee, Y.J., Seo, Y.B., Ajiteru, O., Sung, G.Y., Park, C.H., 2019. Recirculating peritoneal dialysis system using urease-fixed silk fibroin membrane filter with spherical carbonaceous adsorbent. Mater. Sci. Eng.: C 97, 55–66. https://doi.org/10.1016/j.msec.2018.12.021.
Tadda, M.A., Ahsan, A., Shitu, A., ElSergany, M., Arunkumar, T., Jose, B., Daud, N.N., 2016. A review on activated carbon: process, application and prospects. J. Adv. Civil Eng. Practice Res. 2 (1), 7–13.
Taylor, J.E., Lavocah, W., 2017. U.S. Patent Application No. 15/383,130.
Thomas, S., McCubbin, P., 2003. A comparison of the antimicrobial effects of four silver-containing dressings on three organisms. J. Wound Care 12 (3), 101–107. https://doi.org/10.12968/jowc.2003.12.3.26477.
Tripathi, N.K., Singh, V.V., Sathe, M., Thakare, V.B., Singh, B., 2018. Activated carbon fabric: an adsorbent material for chemical protective clothing. Defence Sci. J. 68 (1) https://doi.org/10.14429/dsj.68.11734.
Tsai, C.H., Hsu, H.C., Lin, C.J., 2014. Treatment of chronic wounds with the silver-containing ACF dressing: three cases. J. Med. Cases 5 (11), 587–591. https://doi.org/10.14740/jmc1960w.
Turaga, U., Kendall, R.J., Singh, V., Lalagiri, M., Ramkumar, S.S., 2012. Advances in materials for chemical, biological, radiological and nuclear (CBRN) protective clothing. In: Sparks (Ed.), Advances in Military Textiles and Personal Equipment. Woodhead Publishing, pp. 260–287. https://doi.org/10.1533/9780857095572.2.260.
Tzaneva, V., Mladenova, I., Todorova, G., Petkov, D., 2016. Antibiotic treatment and resistance in chronic wounds of vascular origin. Clujul Med. 89 (3), 365. https://doi.org/10.15386/cjmed-647.
Viaña-Mendieta, P., Sánchez, M.L., Benavides, J., 2022. Rational selection of bioactive principles for wound healing applications: growth factors and antioxidants. Int. Wound J. 19 (1), 100–113. https://doi.org/10.1111/iwj.13602.
Villota, S.M., Lei, H., Villota, E., Qian, M., Lavarias, J., Taylan, V., Agulto, I., Mateo, W., Valentin, M., Denson, M., 2019. Microwave-assisted activation of waste cocoa pod husk by H_3PO_4 and KOH-comparative insight into textural properties and pore development. ACS Omega 4 (4), 7088–7095. https://doi.org/10.1021/acsomega.8b03514.
Vivcharenko, V., Trzaskowska, M., Przekora, A., 2023. Wound dressing modifications for accelerated healing of infected wounds. Int. J. Mol. Sci. 24 (8), 7193. https://doi.org/10.3390/ijms24087193.
Von Blücher, H., Schönfeld, R., Pallaske, F., 2017. U.S. Patent No. 9,782,512. U.S. Patent and Trademark Office, Washington, DC.
Voncina, B., Fras, L.Z., Ristic, T., 2016. Active textile dressings for wound healing. In: van Langenhove, L. (Ed.), Advances in Smart Medical Textiles. Woodhead Publishing, pp. 73–92.
Vuorte, M., Kuitunen, S., Van Tassel, P.R., Sammalkorpi, M., 2023. Equilibrium state model for surfactants in oils: colloidal assembly and adsorption. J. Colloid Interface Sci. 630, 783–794. https://doi.org/10.1016/j.jcis.2022.09.153.
Wang, L., Rao, L., Xia, B., Wang, L., Yue, L., Liang, Y., DaCosta, H., Hu, X., 2018. Highly efficient CO_2 adsorption by nitrogen-doped porous carbons synthesized with low-temperature sodium amide activation. Carbon 130, 31–40. https://doi.org/10.1016/j.carbon.2018.01.003.
White, R., 2013. Would malodour and the role of ACTISORB© Silver 220. Wounds UK 9 (1).
Wu, Y.K., Cheng, N.C., Cheng, C.M., 2019. Biofilms in chronic wounds: pathogenesis and diagnosis. Trends Biotechnol. 37 (5), 505–517. https://doi.org/10.1016/j.tibtech.2018.10.011.
Wu, X., Liu, R., Lao, T.T., 2020. Therapeutic compression materials and wound dressings for chronic venous insufficiency: a comprehensive review. J. Bio. Mater. Res. Part B 108 (3), 892–909. https://doi.org/10.1002/jbm.b.34443.
Yang, C., Shang, S., Shou, D., Lan, G., Dai, F., Hu, E., Yu, K., 2022. Antibiotics-free wound dressing combating bacterial infections: a clean method using silkworm cocoon shell for preparation. Mater. Chem. Phys. 277, 125484 https://doi.org/10.1016/j.matchemphys.2021.125484.
Yao, L., Hui, L., Yang, Z., Chen, X., Xiao, A., 2020. Freshwater microplastics pollution: detecting and visualizing emerging trends based on Citespace II. Chemosphere 245, 125627. https://doi.org/10.1016/j.chemosphere.2019.125627.
Ye, L., He, X., Obeng, E., Wang, D., Zheng, D., Shen, T., Shen, J., Hu, R., Deng, H., 2023. The CuO and AgO co-modified ZnO nanocomposites for promoting wound healing in *Staphylococcus aureus* infection. Mater. Today Bio., 100552 https://doi.org/10.1016/j.mtbio.2023.100552.
Yek, P.N.Y., Peng, W., Wong, C.C., Liew, R.K., Ho, Y.L., Mahari, W.A.W., Azwar, E., Yuan, T.Q., Tabatabaei, M., Aghbashlo, M., Sonne, C., 2020. Engineered biochar via microwave CO_2 and steam pyrolysis to treat carcinogenic Congo red dye. J. Hazard. Mater. 395, 122636 https://doi.org/10.1016/j.jhazmat.2020.122636.
Zhang, L., Weng, C., Zhao, Z., Fu, X., 2017. Extracorporeal shock wave therapy for chronic wounds: a systematic review and meta-analysis of randomized controlled trials. Wound Rep. Regen. 25 (4), 697–706. https://doi.org/10.1111/wrr.12566.
Zhu, X., Liu, X., Liu, Z., 2023. Relieving effect of naringenin on constipation in mice and its effect on intestinal flora in mice. Indian J. Pharm. Sci. 85 (1), 37–43. https://doi.org/10.36468/pharmaceutical-sciences.1066.