Niobium Carbide MXene Augmented Medical Implant Elicits Bacterial Infection Elimination and Tissue Regeneration

*Chuang Yang,[†a] Yao Luo,[†a] Han Lin,[*b] Min Ge,[b] Jianlin Shi,[*b] and Xianlong Zhang[*a]*

†Chuang Yang and Yao Luo contributed equally to this manuscript.

a. Department of Orthopaedics, Shanghai Jiao Tong University Affiliated Sixth People's Hospital, Shanghai Jiao Tong University, Shanghai 200233, P. R. China.

Email: dr_zhangxianlong@sjtu.edu.cn

b. State Key Laboratory of High Performance Ceramics and Superfine Microstructures, Shanghai Institute of Ceramics Chinese Academy of Sciences, Shanghai 200050, P. R. China.

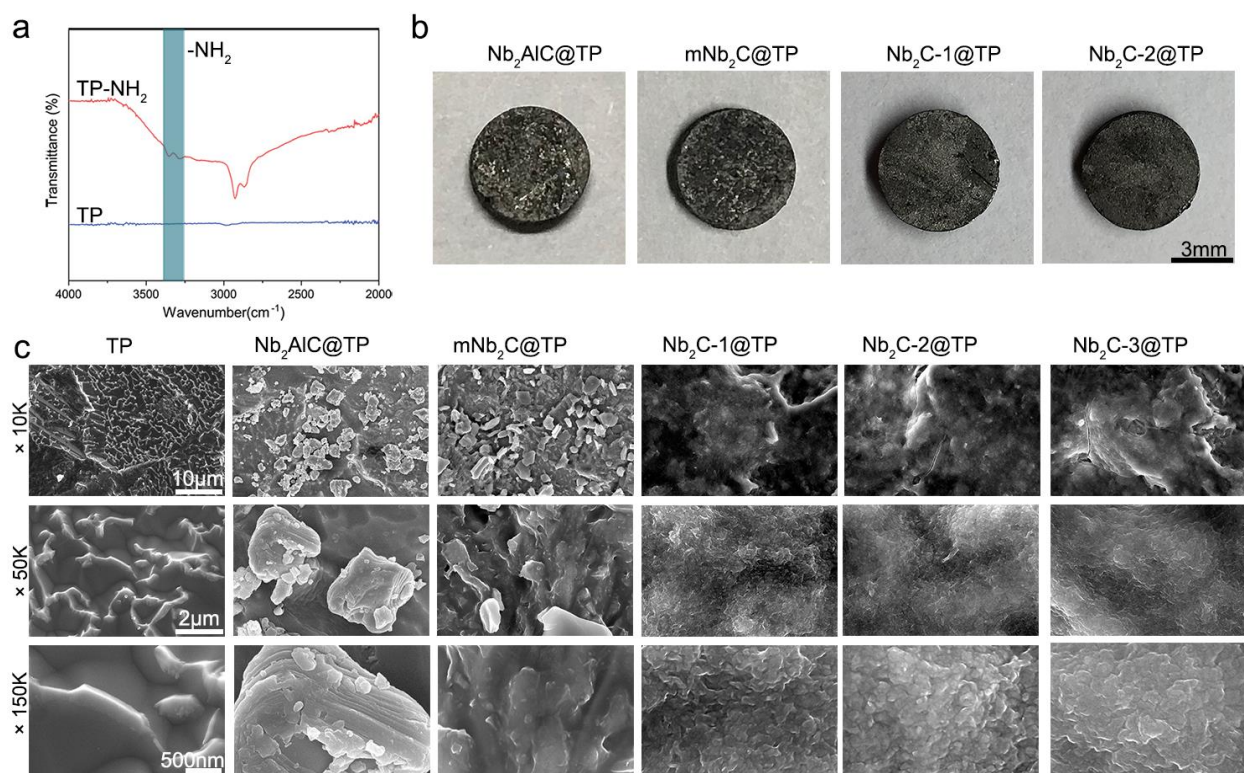Email: linhan@mail.sic.ac.cn; jlshi@mail.sic.ac.cn

Figure S1. (a) FTIR spectra confirming the presence of -NH$_2$ group on the surface of TP-NH$_2$. (b) General photographs of various samples. (c) SEM images of different samples at various magnification.
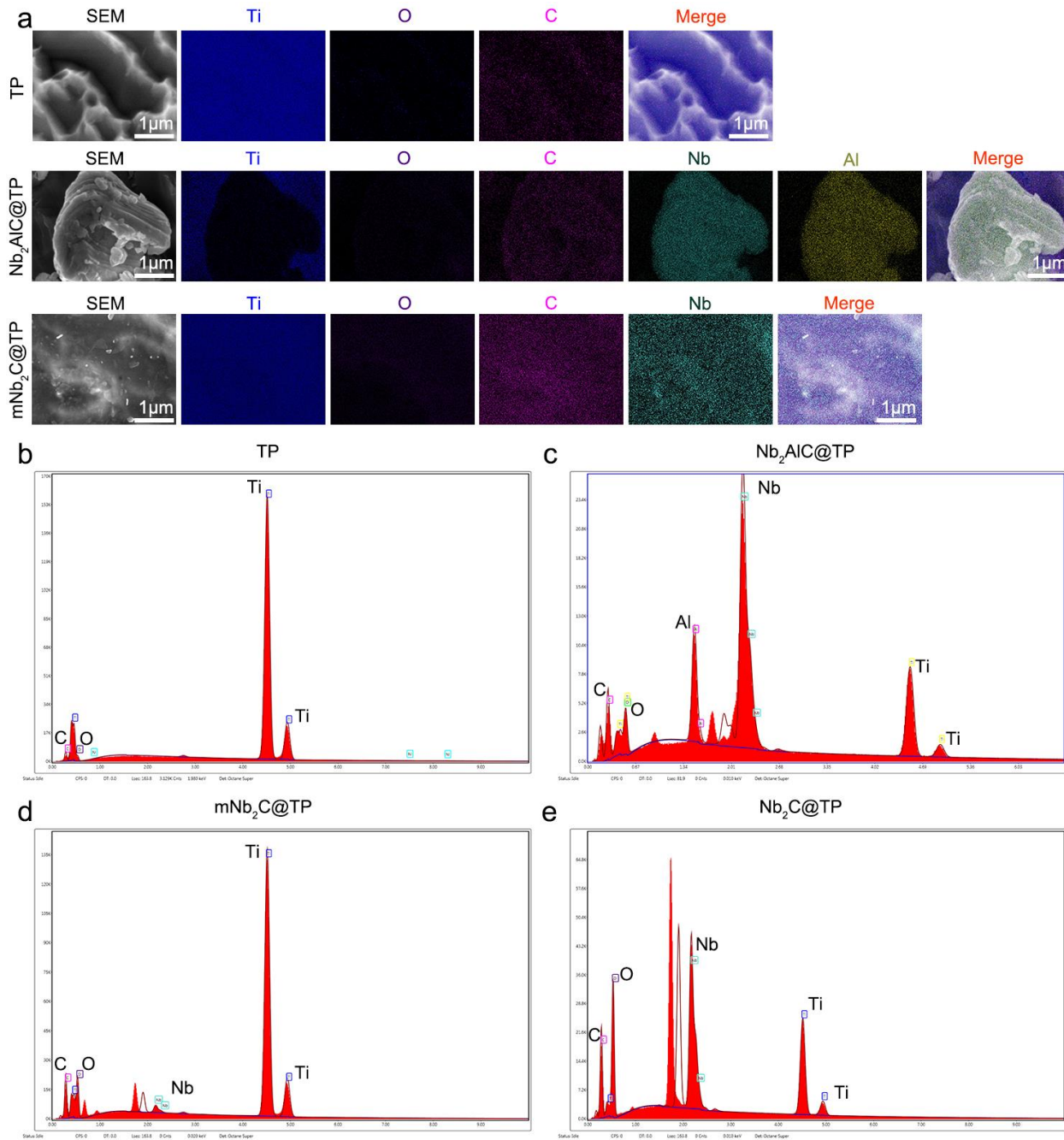
Figure S2. (a) Elemental mapping of TP, Nb₂AlC@TP and mNb₂C@TP. (b) SEM EDS profile confirming the presence of Ti element in TP, with an atomic content of 83.34%±1.87%. (c) SEM EDS profile confirming the presence of Ti, C, Al and Nb in Nb₂AlC@TP, with an atomic content of 27.95±4.21%, 30.73±10.11%, 8.48±4.43% and 17.95±2.58% respectively. (d) SEM EDS profile confirming the presence of Ti, C, and Nb in mNb₂C@TP, with an atomic content of 45.49±1.9%, 17.96±7.23% and 0.42±2.58% respectively. (e) SEM EDS profile confirming the presence of Ti,

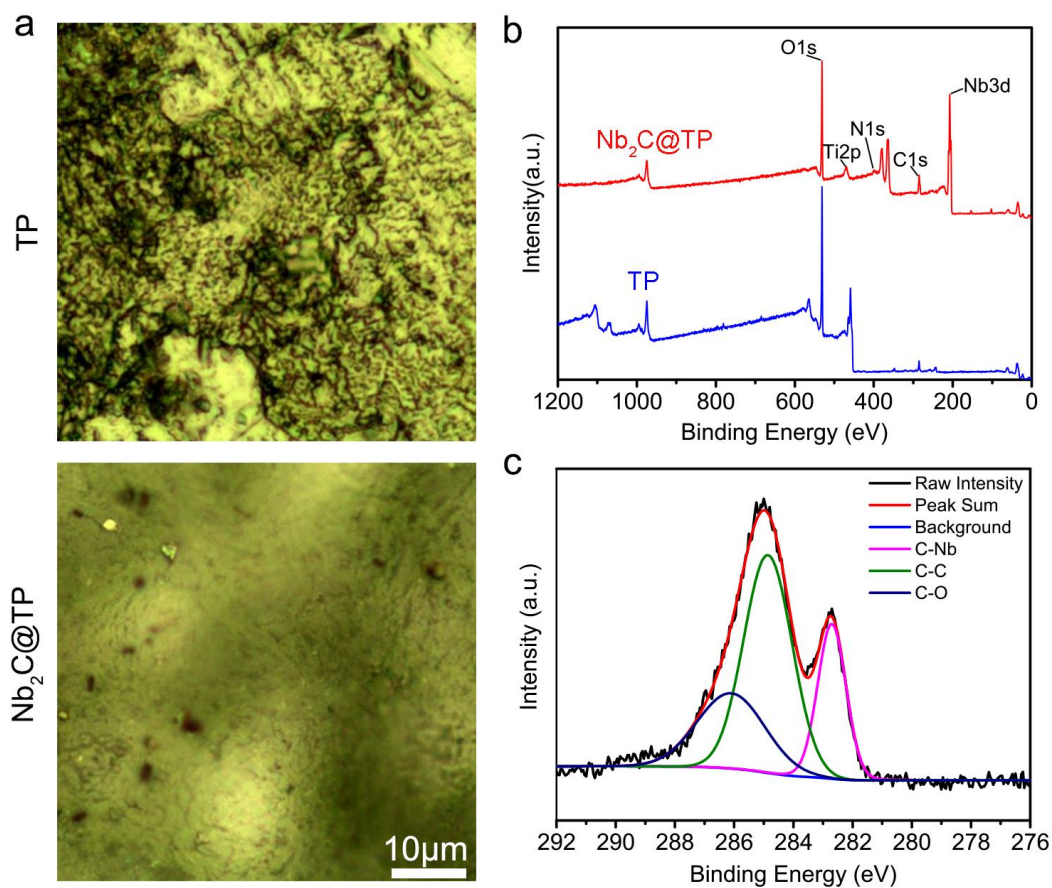C, and Nb in Nb$_2$C@TP, with an atomic content of 10.26±2.33%, 37.2±8.92% and 6±2.09% respectively.

Figure S3. (a) Raman micrographs of TP and Nb$_2$C@TP. (b) XPS spectra of TP and Nb$_2$C@TP including all possible elements. (c) High resolution XPS spectra of C element for Nb$_2$C@TP.
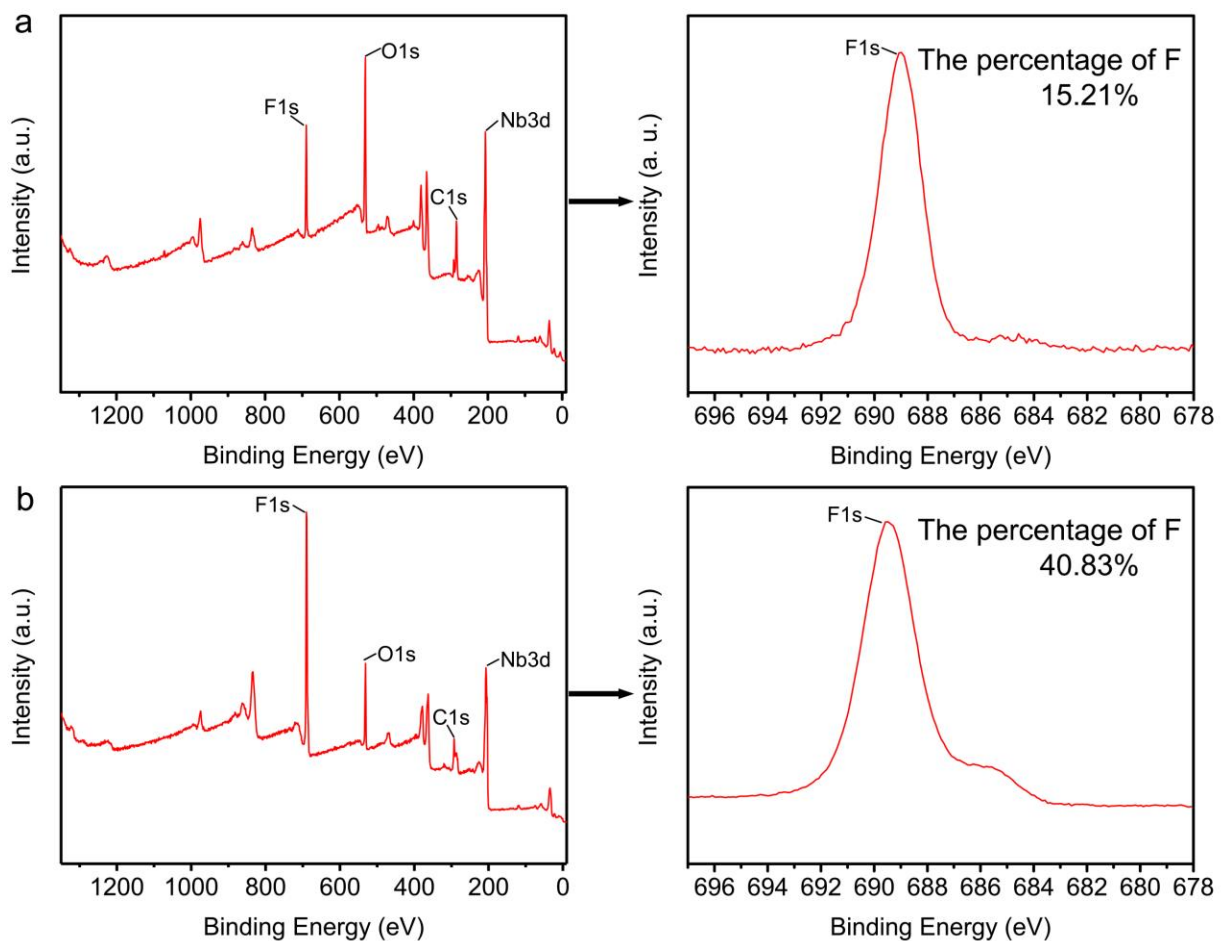
Figure S4. Synthesis of Nb₂C nanosheets with various percentages of fluorine (F) element. (a) XPS spectra of all possible elements and high-resolution spectra of F element for Nb₂C nanosheets containing 15.21% F element. (b) XPS spectra of all possible elements and high-resolution spectra of F element for Nb₂C nanosheets containing 40.83% F element.
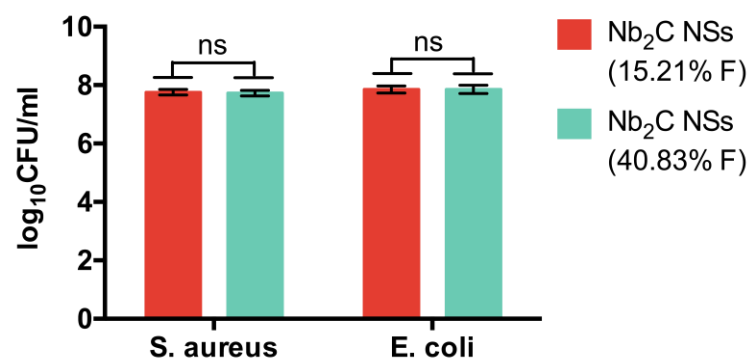
Figure S5. Bacterial growth after co-culture with Nb_2C nanosheets with different percentages of F element. ns, P>0.05, not significant.
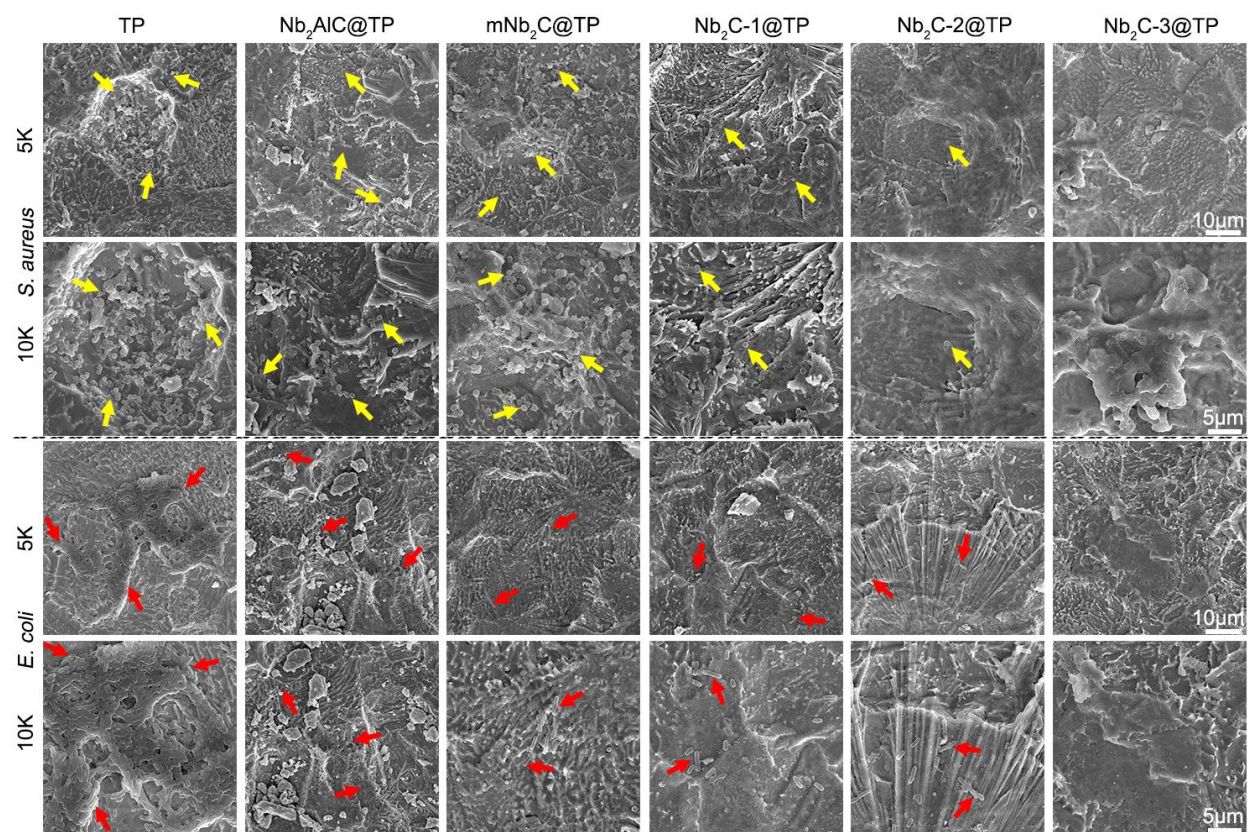
Figure S6. SEM images of biofilm at different magnifications. Yellow arrows indicate *S. aureus*. Red arrows indicate *E. coli*.
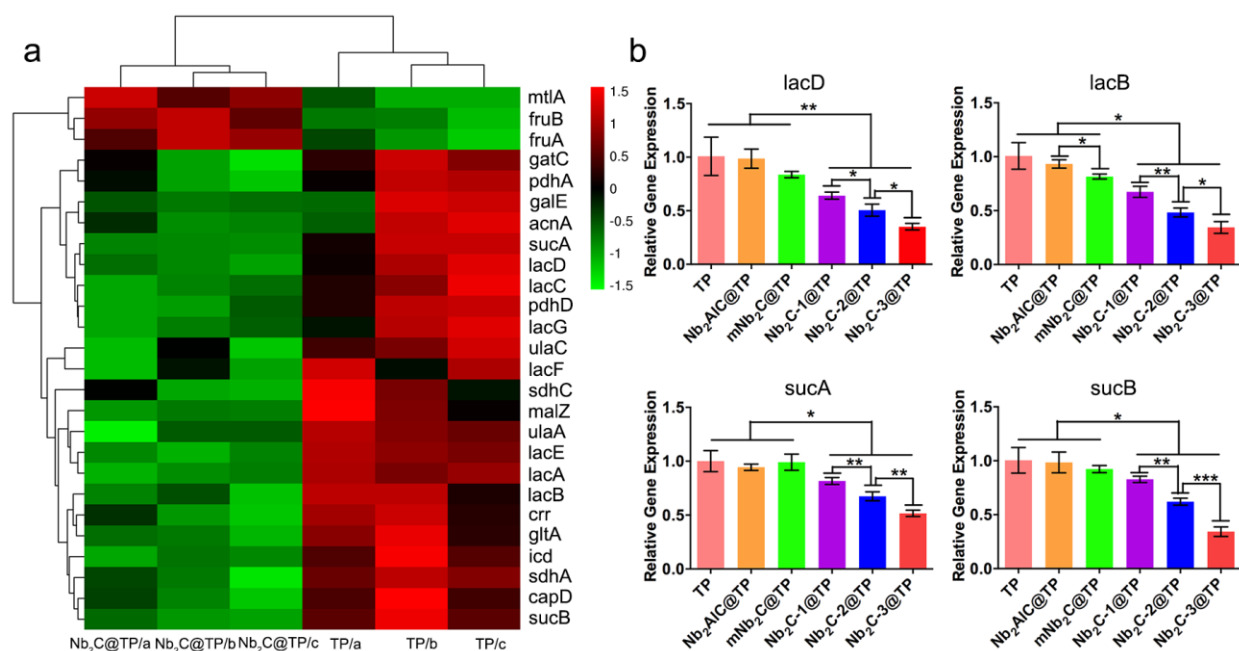
Figure S7. (a) Hierarchical clustering heatmap of DEGs in energy metabolism related pathways. (b) RT-PCR results of typical genes in energy metabolism pathways.
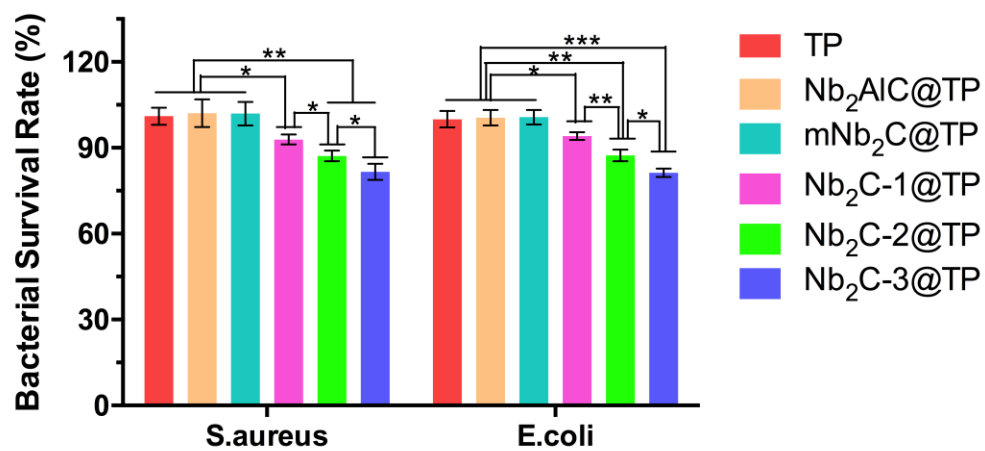
Figure S8. The survival rate of planktonic bacteria co-cultured with different samples.
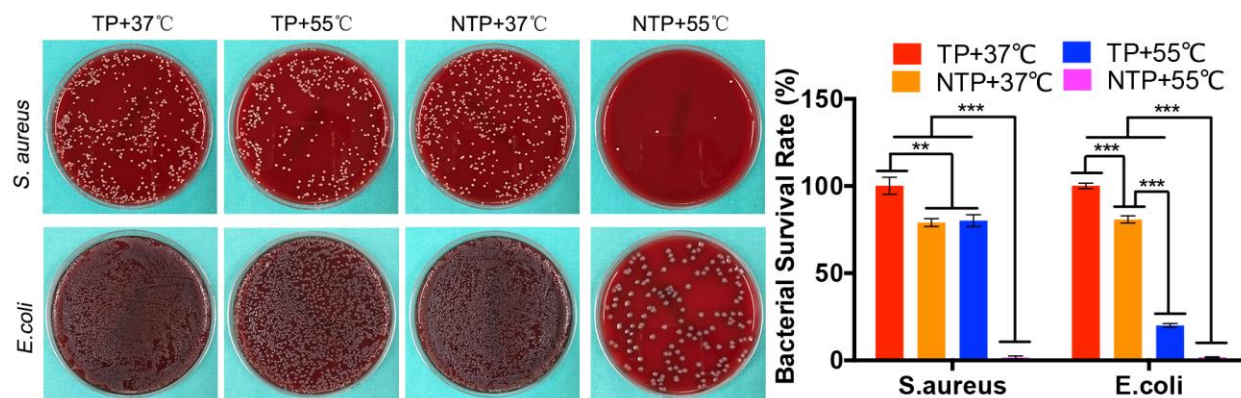
Figure S9. **Increased Sensitivity to Heat of Bacteria Treated with NTP.** The planktonic bacterial colonies and bacterial survival rate in TP or NTP system when exposed to elevated temperature.
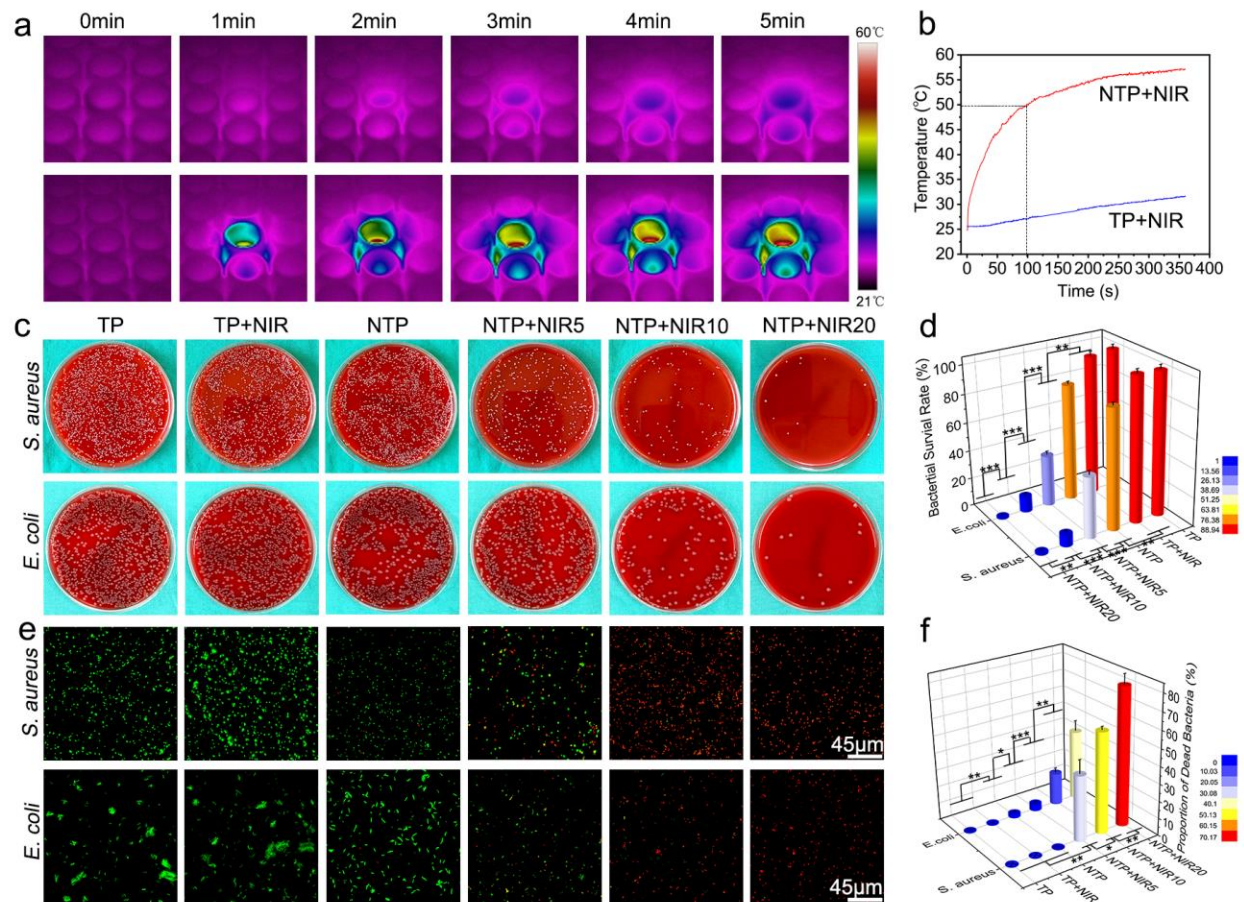
Figure S10. (a,b) *In vitro* thermographic images and temperature curves of TP and NTP under NIR irradiation at the power density of 0.75 W cm^{-2}. (c,d) Representative culture images of bacterial colonies from planktonic bacteria and corresponding bacterial survival rate (NIR5, NIR10 and NIR20 represent irradiated by NIR for 5, 10 and 20 minutes). (e,f) Fluorescent pictures of planktonic bacteria and corresponding quantitative analysis of dead bacteria.
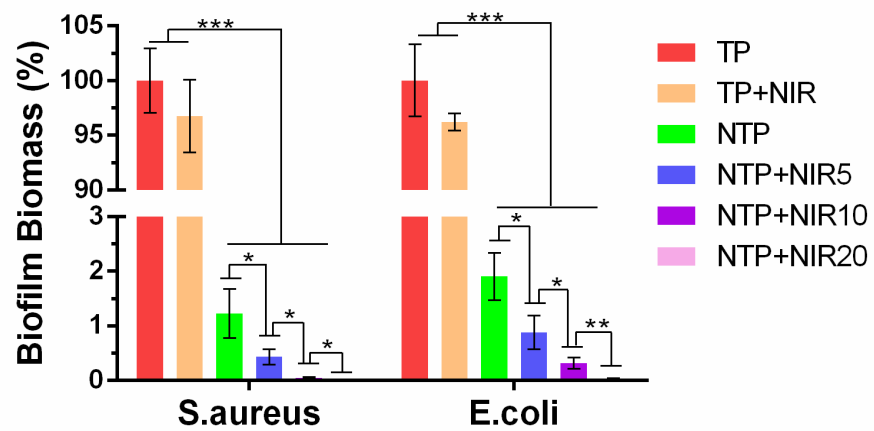
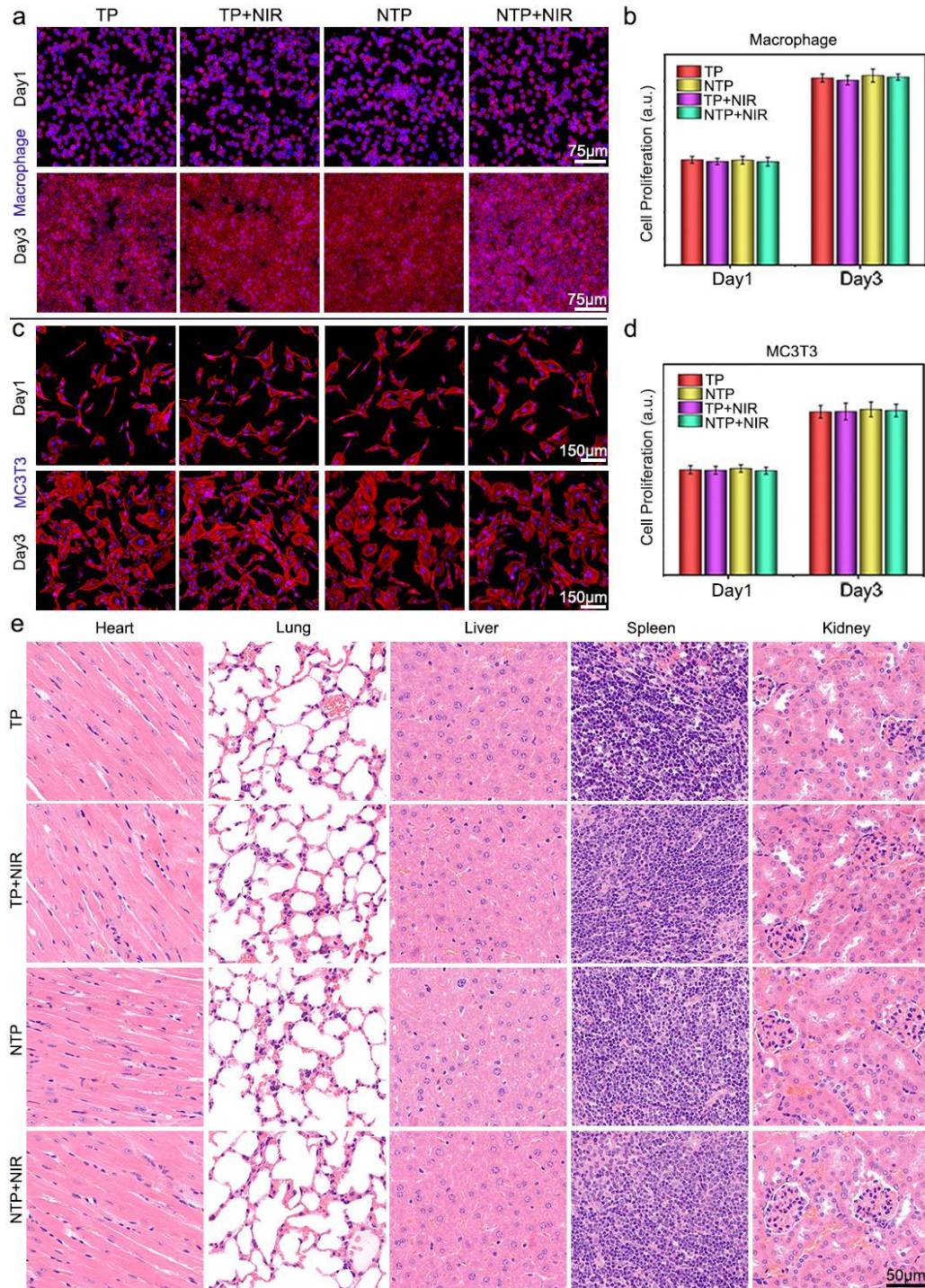**Figure S11**. Biofilm biomass after NIR irradiation.

Figure S12. (a,c) Fluorescent staining of mcrophages and fibroblasts after different treatments. Blue indicates cell nucleis, and red indicates cytoskeleton. (b,d) Cell viability analysis from CCK-8 results. (e) HE staining of pathological sections from major organs in different group.
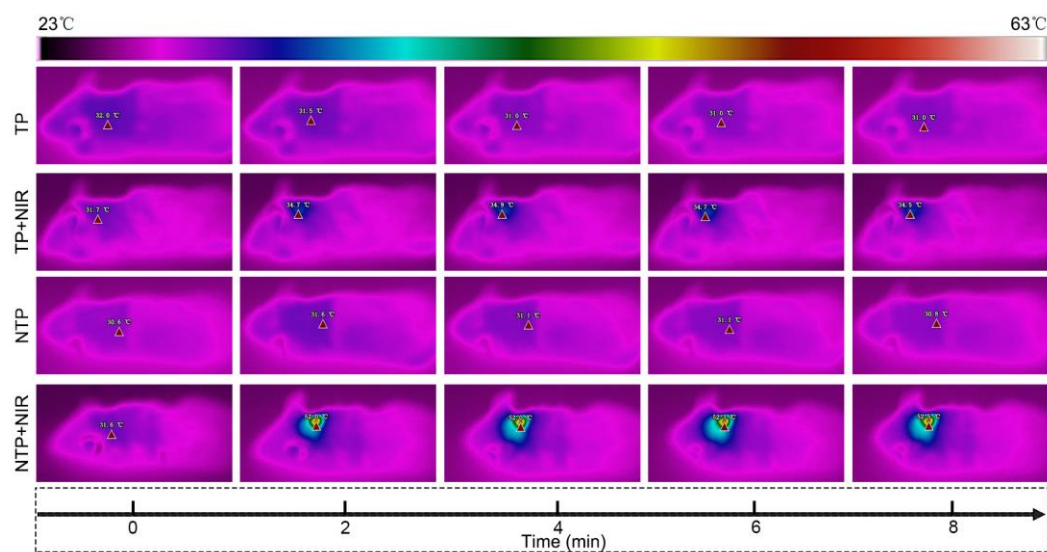
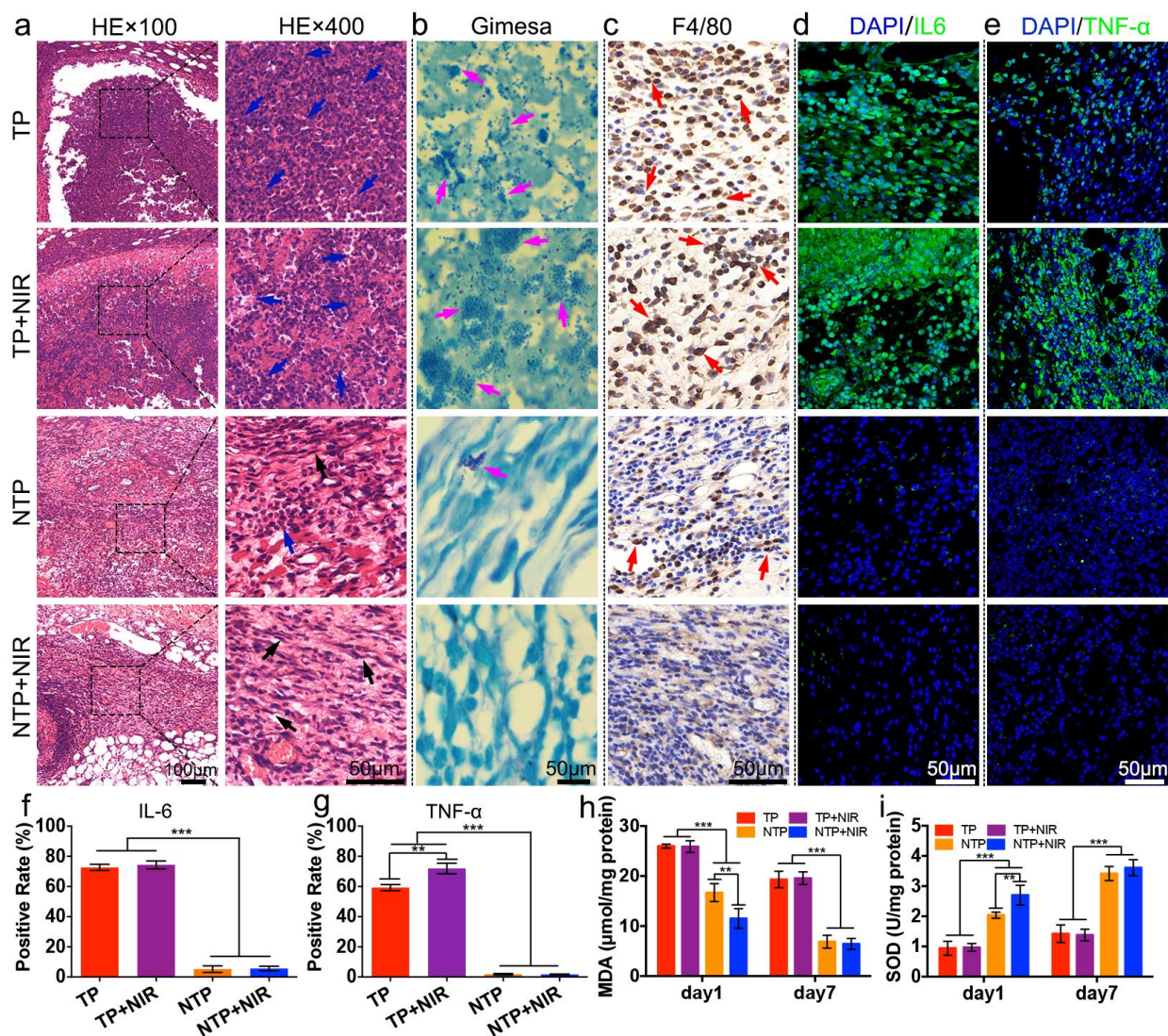**Figure S13**. *In vivo* infrared imaging pictures.

Figure S14. *In vivo* anti-inflammatory and bactericidal effect of Nb₂C@TP. (a) HE staining. The images in the second column are the magnified ones of the selected squares in the first column. The blue arrows indicate infiltrated neutrophils, black arrows indicate fibroblasts. (b) Gimesa staining. The pink arrows indicate bacteria. (c) Immunohistochemical staining for F4/80. The red arrows indicate the F4/80 positive cells. (d,e) Immunofluorescence staining for IL-6 and TNF-α. (f,g) quantitative analysis of IL-6 and TNF-α positive cells. (h,i) SOD and MDA content analysis in the implant surrounding area.
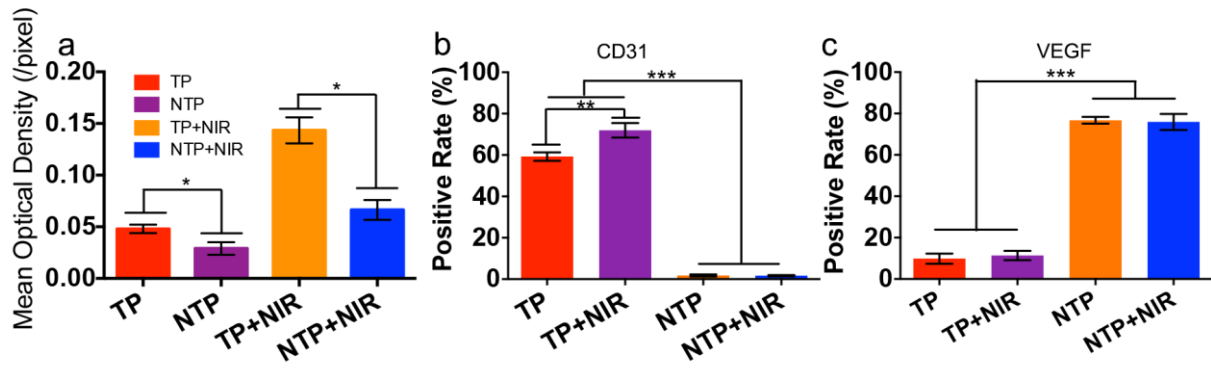
Figure S15. (a) Intracellular ROS levels in macrophages. (b,c) CD31 and VEGF immunofluorescence positive rate.

Table S1. Primes used for RT-PCR.

Gene name	Sense Primer
HtrA-F	GTAGGTAATCCACTTGGTGTAGAC
HtrA-R	CCTTCTCTATTGACGACAGCAC
sucB-F	ACGACAATACTCCACAACAAAATG
sucB-R	ACTTACTTCAGCAAGATTCACACC
sucA-F	AGCAGCACAAGATGATACACAAC
sucA-R	ACCACCCGTAGAATAGCCTTTC
sak-F	TTTGATGGTAAATGTGACTGGAG
sak-R	CGCTTGGATCTAATTCAACTACTC
agrC-F	AAATTGATGACCCTATCATTCGC
agrC-R	ATAGACCTAAACCACGACCTTC
agrA-F	GCCCTCGCAACTGATAATCC
agrA-R	GGTCATGCTTACGAATTTCACTG
lacB-F	CGTAACAGAAGGACAGGAAGTTG
lacB-R	TCTAGTCATATATCCAGAGCGTTC
lacD-F	AGAGGAAGCGGCACAACAC
lacD-R	AGCACCAGACCATGTAGCAC
16SrRNA-F	GGCCTTGCGCGATTGTATAT
16SrRNA-R	GTGGCGGATCATCTTCTCAGA